CATALYZING A SUSTAINABLE RENAISSANCE OF AMERICAN MINING

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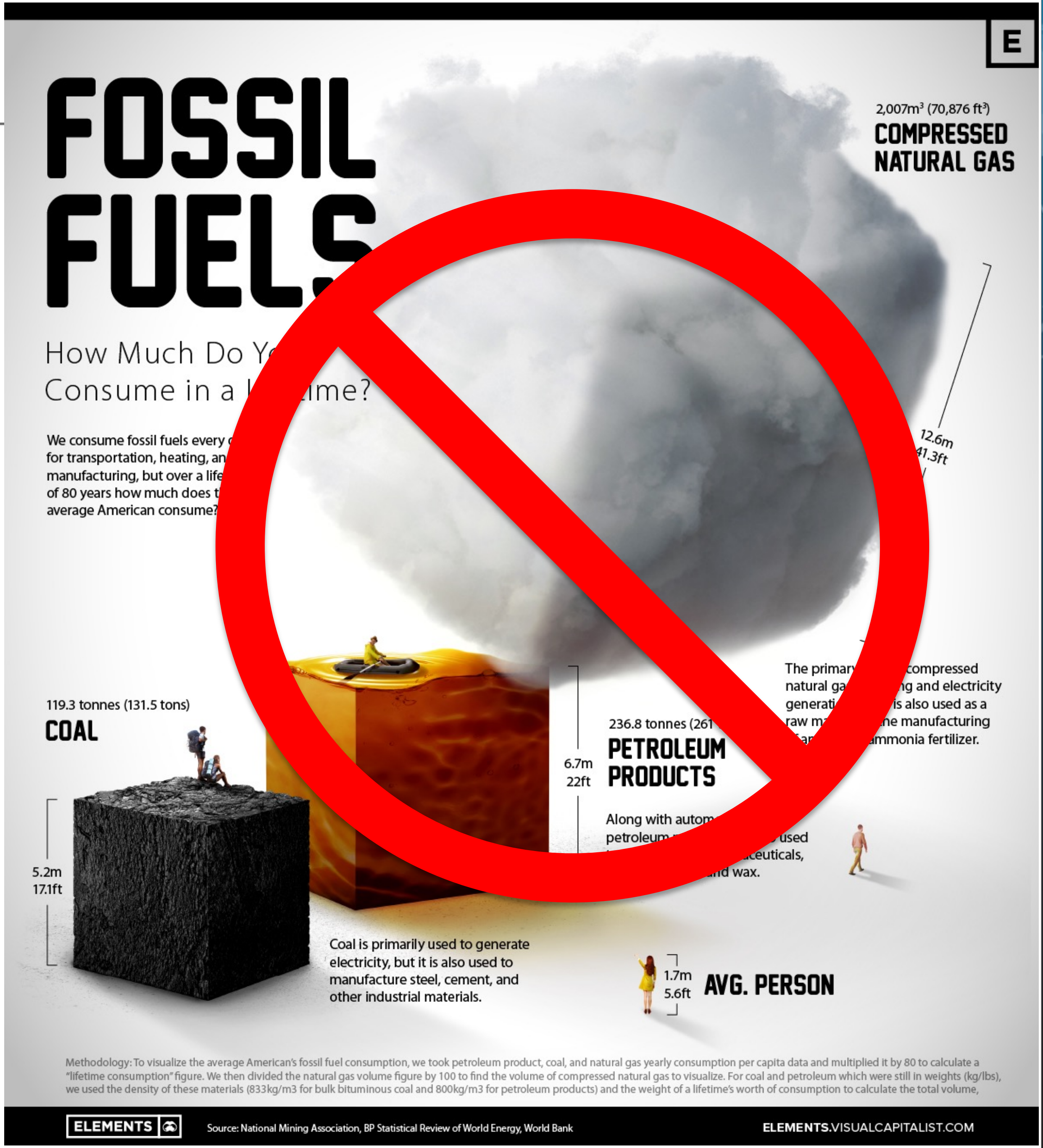
ARPA-E
CHANGING WHAT'S POSSIBLE

It's time to wake up!!

What am I going to talk about?

- A bit about ARPA-E
- A peek into the abyss
- A look at white spaces for those who are not faint of heart



https://elements.visualcapitalist.com/a-lifetimes-consumption-of-fossil-fuels-visualized/

Visual Capitalist

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Most importantly

- I'm here to start a conversation
- I don't have the answers
- But do know
  - Business as usual won't cut it and
  - My generation isn't going to solve the problem
- I'm looking for your **bold** suggestions

Btw - This is not an official view of the DOE or ARPA-E

Who, what and how do we fund?

Who?

- Academics, big companies, small companies, National Labs

What?

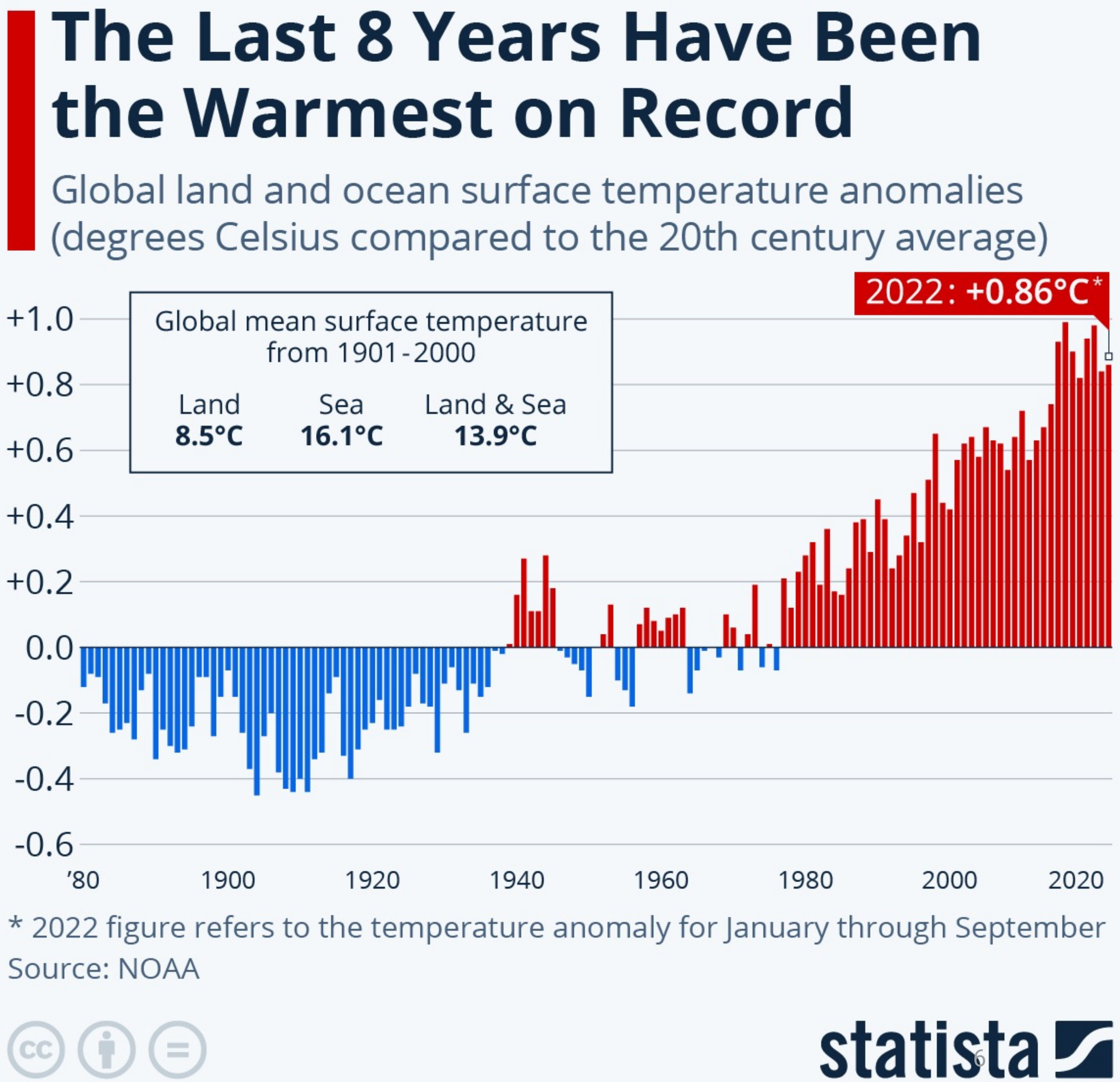
- Transformative projects

How?

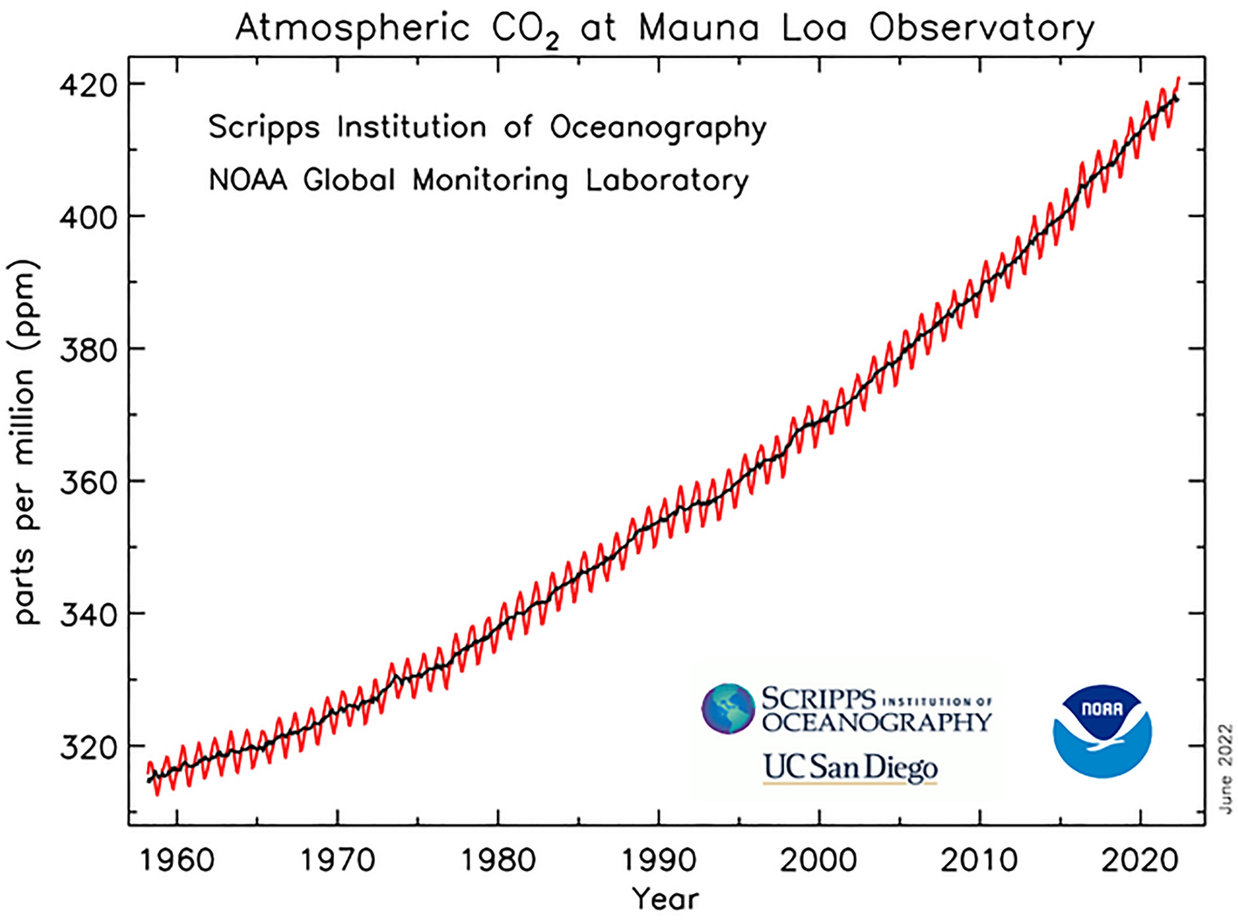
- CRADAs through programs
- Grants through special topics
- SBIR/STTR (we call SEED)

THE ABYSS

The Climate


The Last 8 Years Have Been the Warmest on Record
Global land and ocean surface temperature anomalies (degrees Celsius compared to the 20th century average)
2022: +0.86°C*
Global mean surface temperature from 1901 - 2000
Land
8.5°C
Sea
16.1°C
Land & Sea
13.9°C
+1.0
+0.8
+0.6
+0.4
+0.2
0.0
-0.2
-0.4
-0.6
'80
1900
1920
1940
1960
1980
2000
2020
* 2022 figure refers to the temperature anomaly for January through September
Source: NOAA
statista

Could T depend on $[CO_2]$?



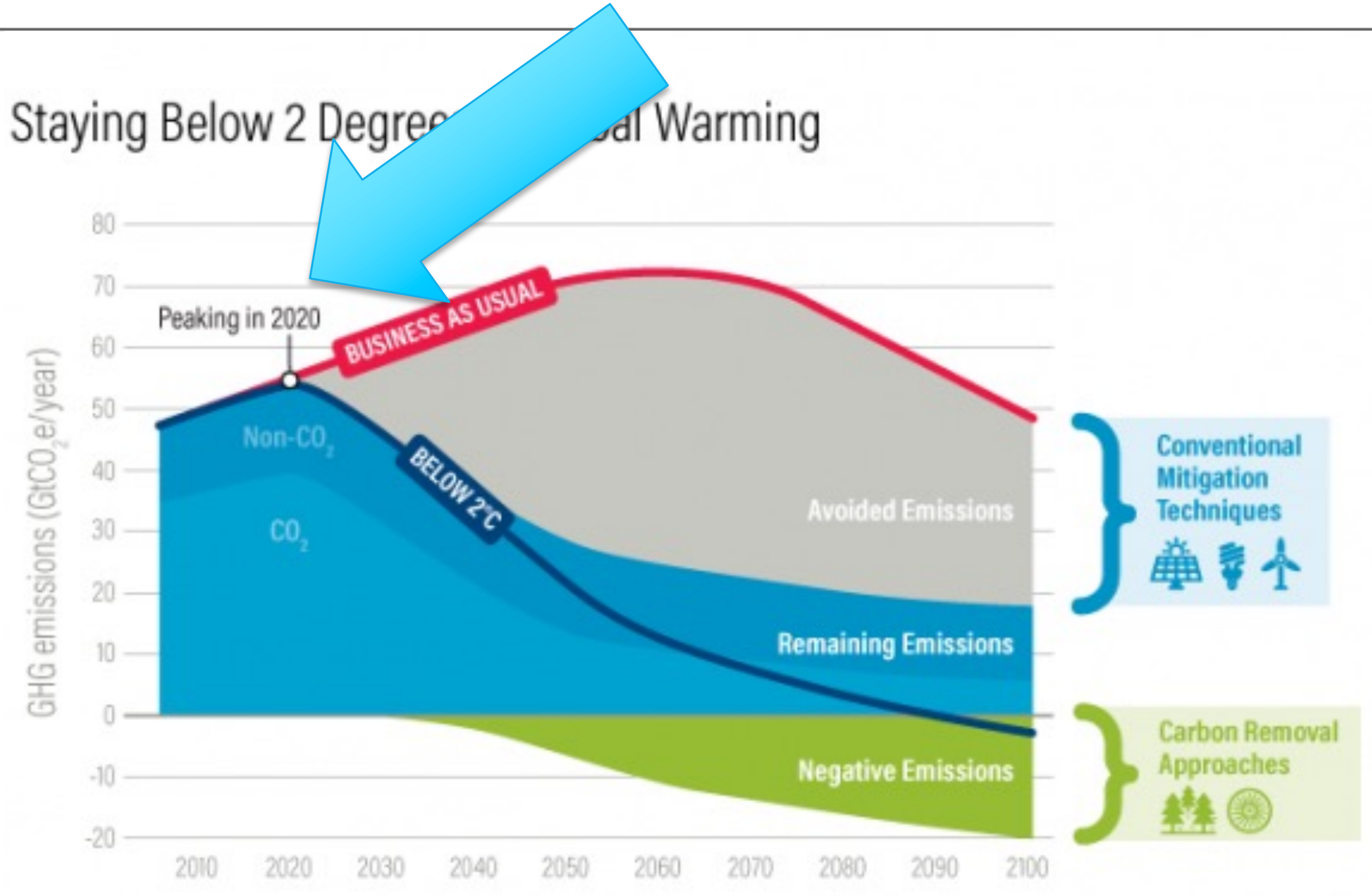
Climatic Change: Are We on the Brink of a Pronounced Global Warming?

WALLACE S. BROECKER Authors Info & Affiliations

SCIENCE • 8 Aug 1975 • Vol 189, Issue 4201 • pp. 460-463 • DOI: 10.1126/science.189.4201.460

August **1975 !!**

CO_2 and 2°C



Note: This is a notional scenario consistent with an at least 66 percent chance of limiting global warming to below 2°C. Some residual gross greenhouse gas emissions (both CO_2 and non-CO_2) will remain at the end of the century even with ambitious climate action because they are too difficult or costly to remove entirely. Once negative emissions exceed those that remain net zero emissions is reached.

Source: Adapted from a visual in The UNEP Gap Report 2017 (Figure 7.2)

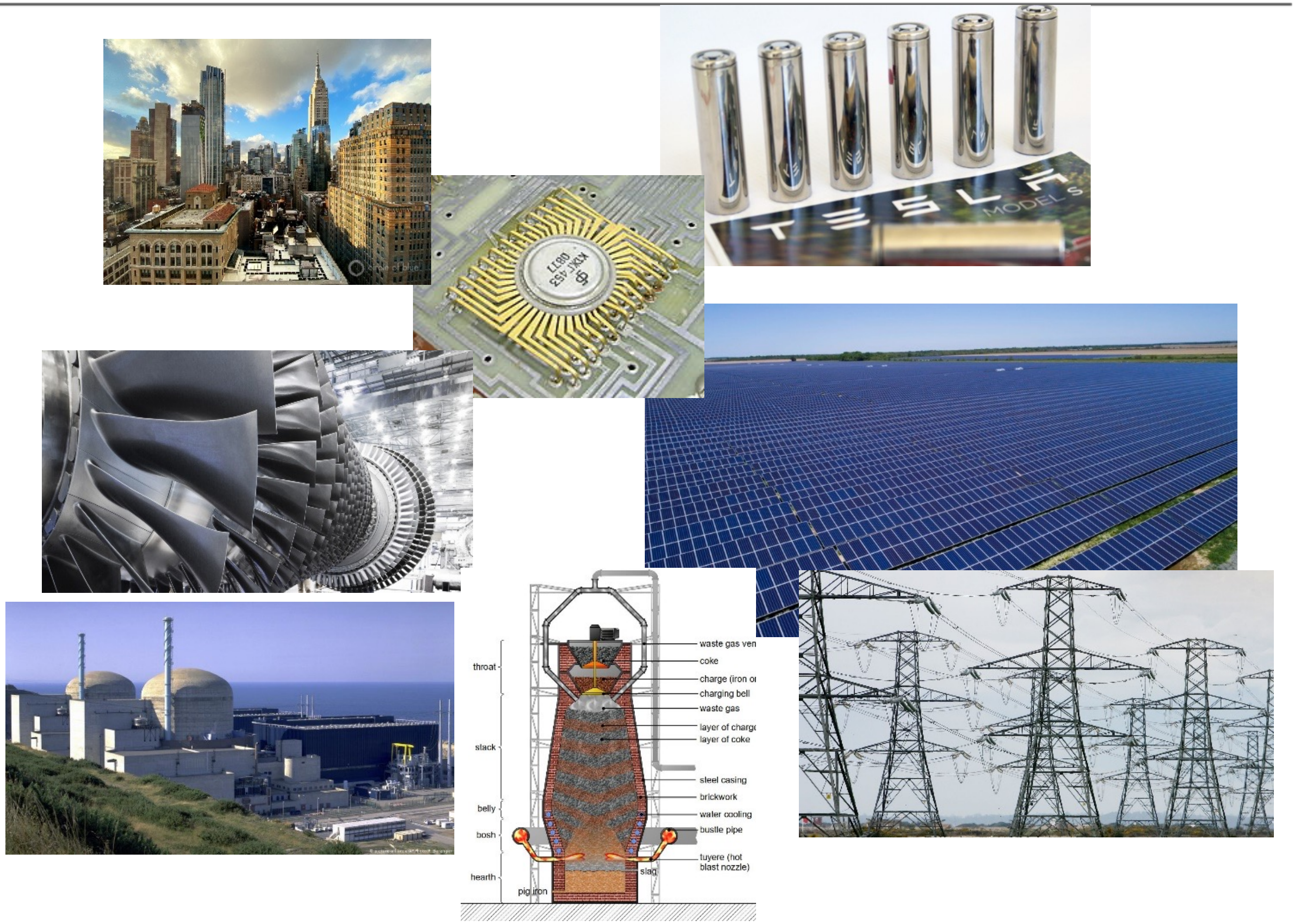
WORLD RESOURCES INSTITUTE

We have the Tech for Clean Energy

So, what's wrong?

In the Beginning…

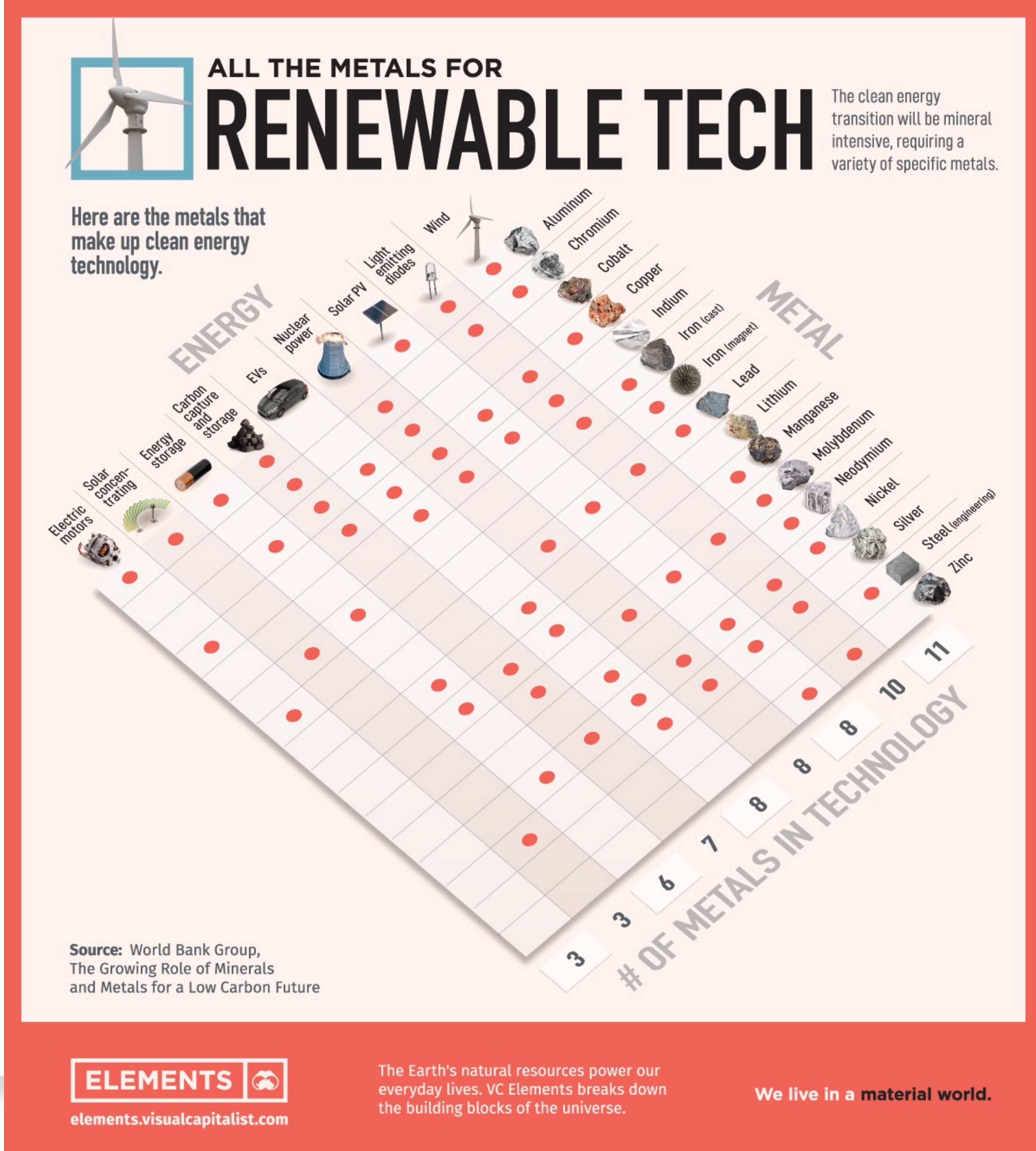
There are mountains and rocks



Then comes everything for the energy transition

We need to move "from BIG Oil to BIG Shovels"

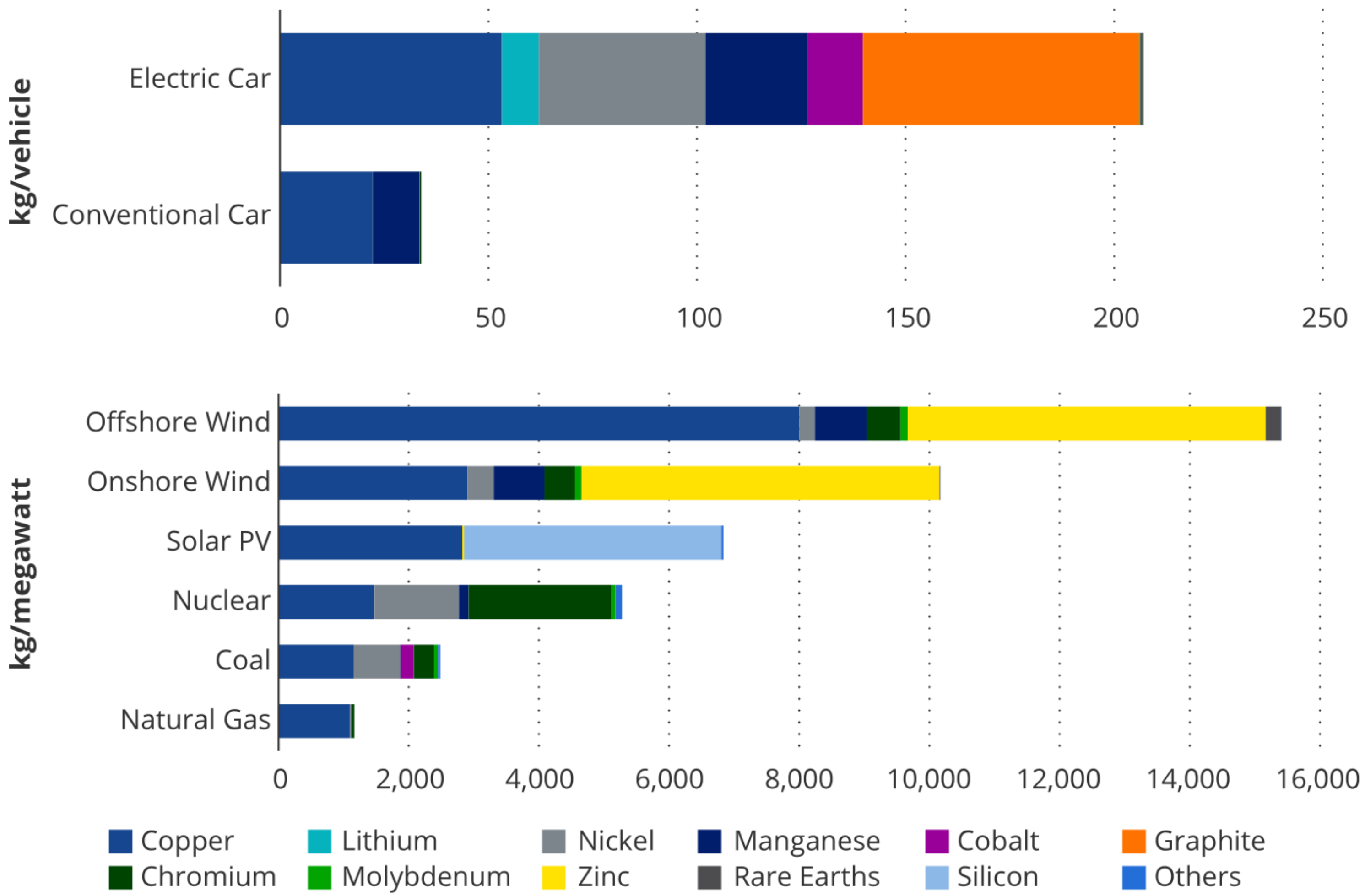
— Daniel Yergin



Metals required for EV's and Clean Energy

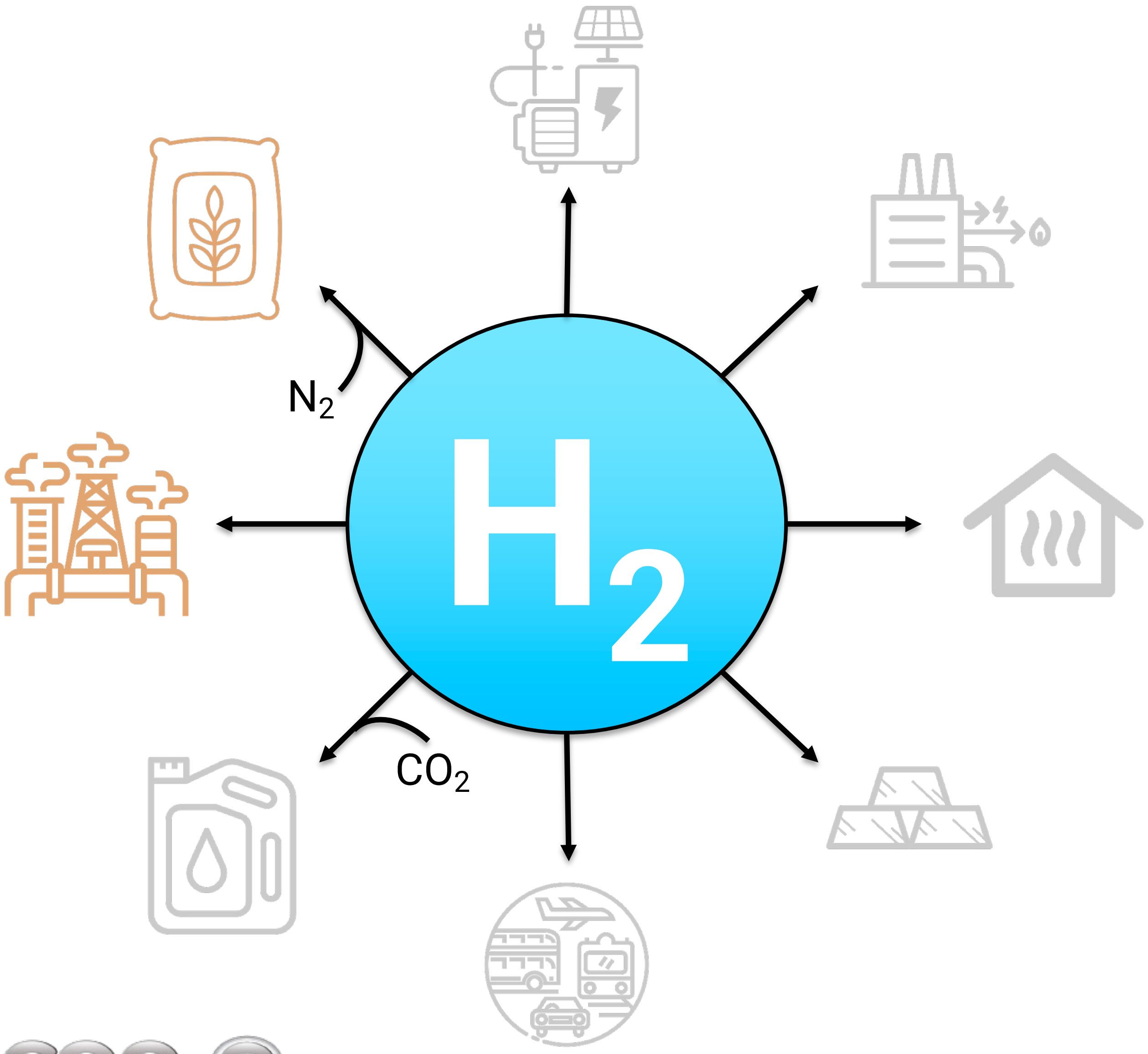
Globally
>1,000,000,000 cars
>400,000,000 trucks

Global Energy Use
170,000 TWh



Source: IEA (2021), The Role of Critical Minerals in Clean Energy Transitions, IEA, Paris. Chart for illustrative purposes only.

Another Challenge: will hydrogen meet the moment?



Today

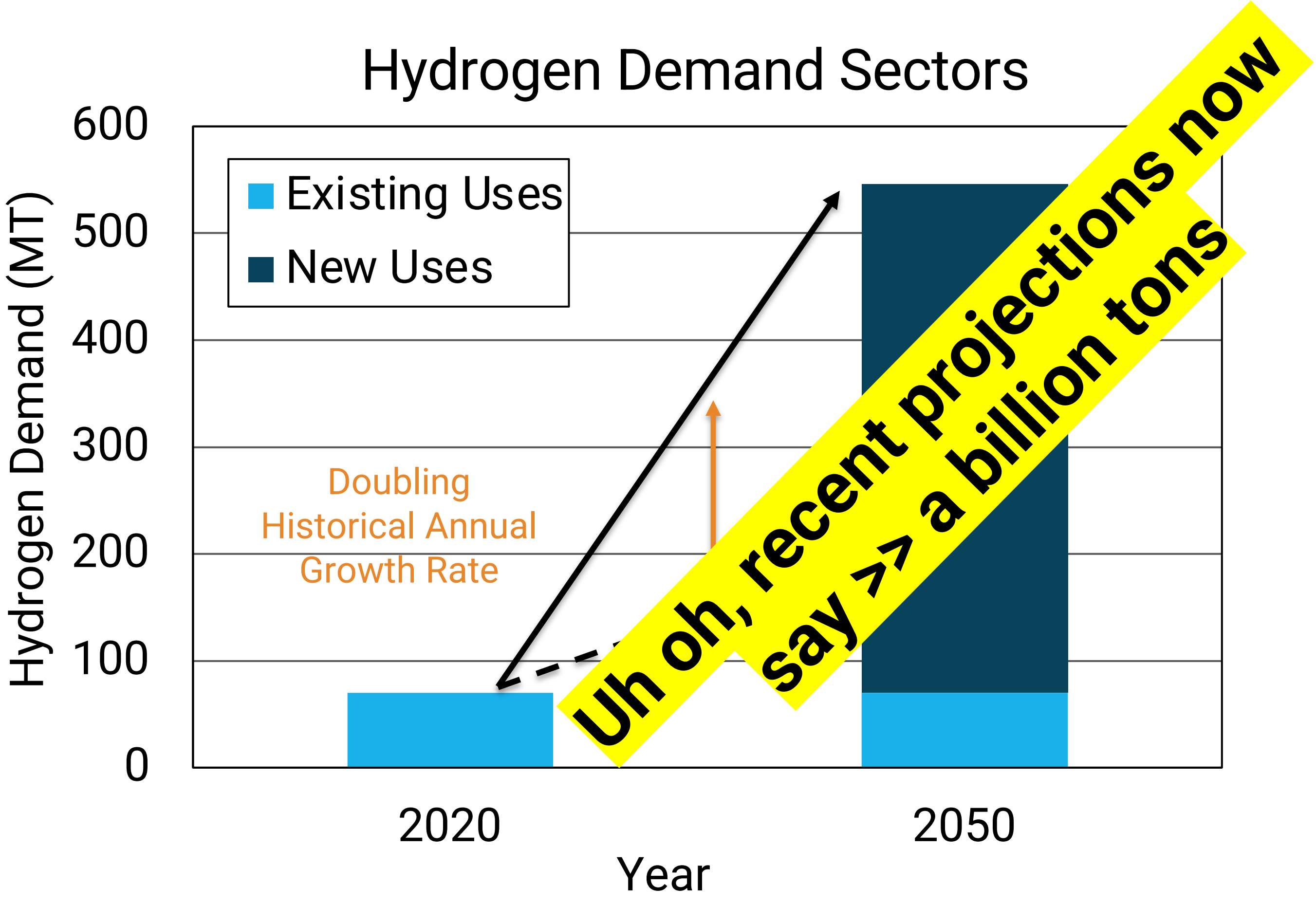
70 Mt per year

1.5% global emissions

2% global primary energy

International Energy Agency. *The Future of Hydrogen Seizing Today's Opportunities.* June 2019.

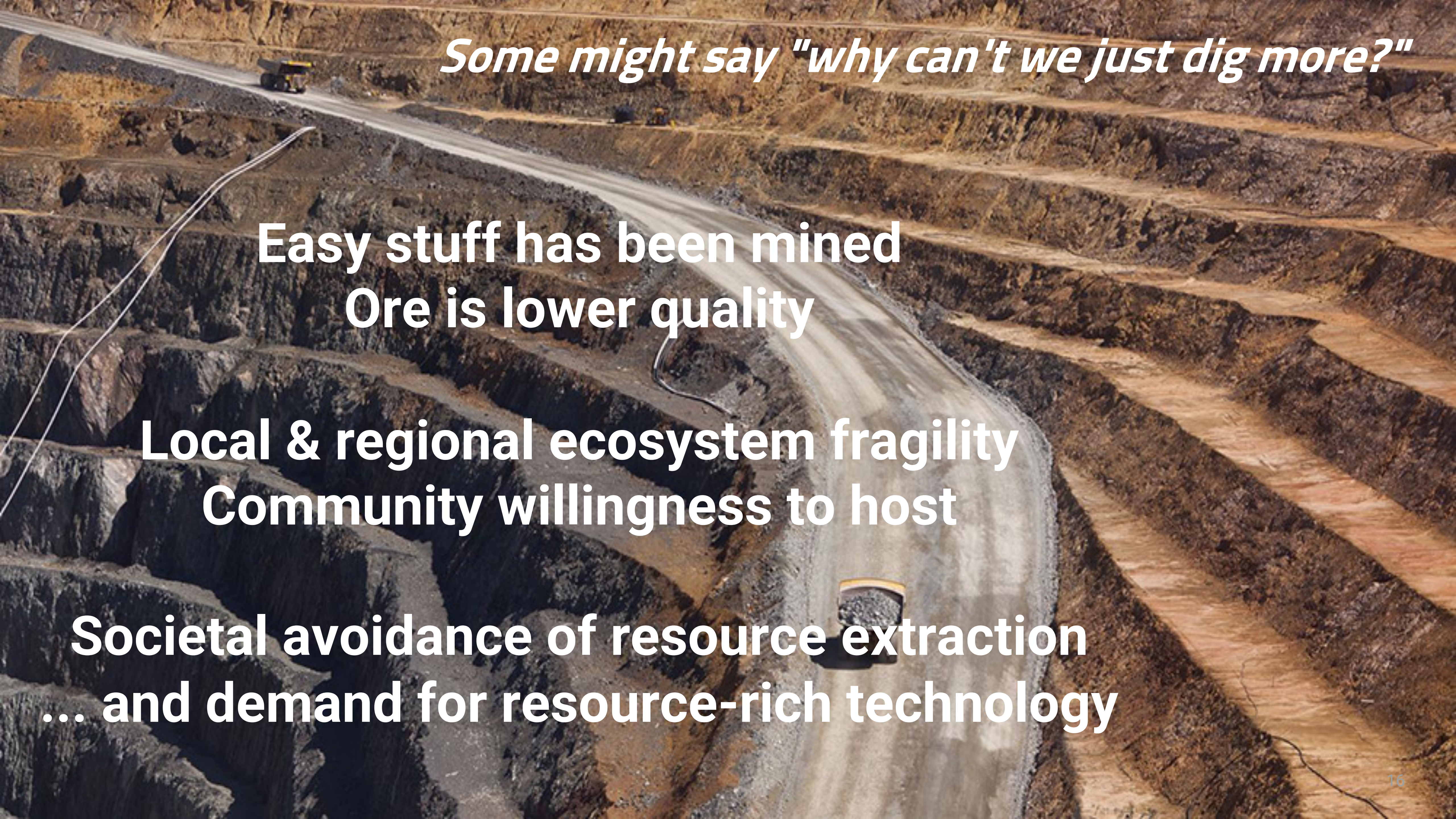
Overhauling an entire industry in 30 years...



1/5 global CO_2 emissions to be stored for blue hydrogen

> 3 TW renewable energy capacity for green hydrogen **+ basically all of the platinum group metals we know of**

International Energy Agency. *The Future of Hydrogen- Seizing Today's Opportunities*. June 2019. Hydrogen Council. *Hydrogen Scaling Up*. November 2017.


Some might say "why can't we just dig more?"
Easy stuff has been mined
Ore is lower quality
Local & regional ecosystem fragility
Community willingness to host
Societal avoidance of resource extraction
... and demand for resource-rich technology

The US Not a Player

Manganese 100%

Rare Earths 100%

Vanadium 94%

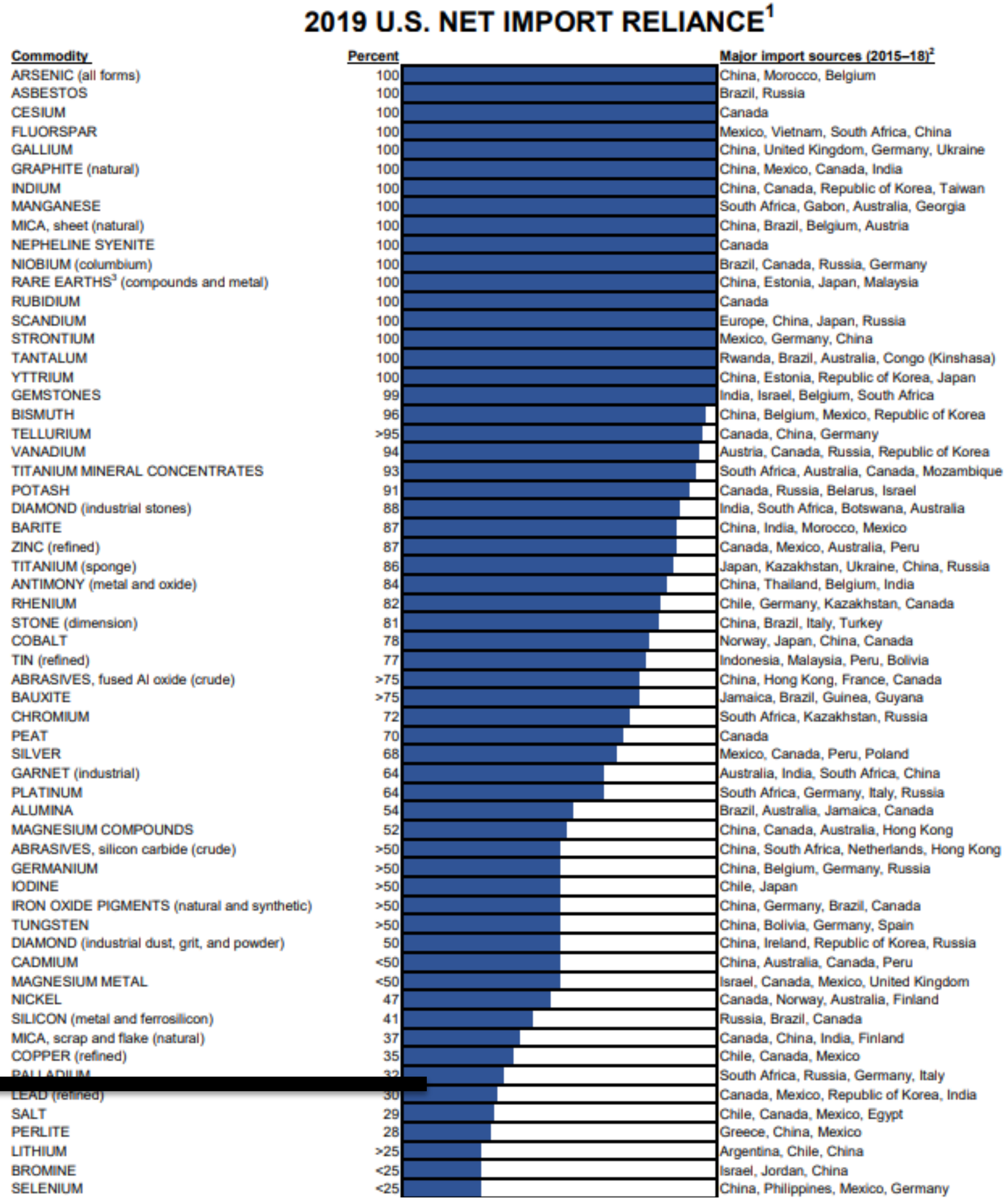
Cobalt 78%
>90% of base metal is imported

Magnesium 52%

Maximum US Reliance on Oil/Gas Imports Was 30% in 2005

Nickel 47%
of class 1 nickel is imported

Lithium 25%
***100% of battery grade**



2019 U.S. NET IMPORT RELIANCE[1]

Commodity	Percent	Major import sources (2015–18)[2]
ARSENIC (all forms)	100	China, Morocco, Belgium
ASBESTOS	100	Brazil, Russia
CESIUM	100	Canada
FLUORSPAR	100	Mexico, Vietnam, South Africa, China
GALLIUM	100	China, United Kingdom, Germany, Ukraine
GRAPHITE (natural)	100	China, Mexico, Canada, India
INDIUM	100	China, Canada, Republic of Korea, Taiwan
MANGANESE	100	South Africa, Gabon, Australia, Georgia
MICA, sheet (natural)	100	China, Brazil, Belgium, Austria
NEPHELINE SYENITE	100	Canada
NIOBIUM (columbium)	100	Brazil, Canada, Russia, Germany
RARE EARTHS[3] (compounds and metal)	100	China, Estonia, Japan, Malaysia
RUBIDIUM	100	Canada
SCANDIUM	100	Europe, China, Japan, Russia
STRONTIUM	100	Mexico, Germany, China
TANTALUM	100	Rwanda, Brazil, Australia, Congo (Kinshasa)
YTTRIUM	100	China, Estonia, Republic of Korea, Japan
GEMSTONES	99	India, Israel, Belgium, South Africa
BISMUTH	96	China, Belgium, Mexico, Republic of Korea
TELLURIUM	>95	Canada, China, Germany
VANADIUM	94	Austria, Canada, Russia, Republic of Korea
TITANIUM MINERAL CONCENTRATES	93	South Africa, Australia, Canada, Mozambique
POTASH	91	Canada, Russia, Belarus, Israel
DIAMOND (industrial stones)	88	India, South Africa, Botswana, Australia
BARITE	87	China, India, Morocco, Mexico
ZINC (refined)	87	Canada, Mexico, Australia, Peru
TITANIUM (sponge)	86	Japan, Kazakhstan, Ukraine, China, Russia
ANTIMONY (metal and oxide)	84	China, Thailand, Belgium, India
RHENIUM	82	Chile, Germany, Kazakhstan, Canada
STONE (dimension)	81	China, Brazil, Italy, Turkey
COBALT	78	Norway, Japan, China, Canada
TIN (refined)	77	Indonesia, Malaysia, Peru, Bolivia
ABRASIVES, fused Al oxide (crude)	>75	China, Hong Kong, France, Canada
BAUXITE	>75	Jamaica, Brazil, Guinea, Guyana
CHROMIUM	72	South Africa, Kazakhstan, Russia
PEAT	70	Canada
SILVER	68	Mexico, Canada, Peru, Poland
GARNET (industrial)	64	Australia, India, South Africa, China
PLATINUM	64	South Africa, Germany, Italy, Russia
ALUMINA	54	Brazil, Australia, Jamaica, Canada
MAGNESIUM COMPOUNDS	52	China, Canada, Australia, Hong Kong
ABRASIVES, silicon carbide (crude)	>50	China, South Africa, Netherlands, Hong Kong
GERMANIUM	>50	China, Belgium, Germany, Russia
IODINE	>50	Chile, Japan
IRON OXIDE PIGMENTS (natural and synthetic)	>50	China, Germany, Brazil, Canada
TUNGSTEN	>50	China, Bolivia, Germany, Spain
DIAMOND (industrial dust, grit, and powder)	50	China, Ireland, Republic of Korea, Russia
CADMIUM	<50	China, Australia, Canada, Peru
MAGNESIUM METAL	<50	Israel, Canada, Mexico, United Kingdom
NICKEL	47	Canada, Norway, Australia, Finland
SILICON (metal and ferrosilicon)	41	Russia, Brazil, Canada
MICA, scrap and flake (natural)	37	Canada, China, India, Finland
COPPER (refined)	35	Chile, Canada, Mexico
PALLADIUM	32	South Africa, Russia, Germany, Italy
LEAD (refined)	30	Canada, Mexico, Republic of Korea, India
SALT	29	Chile, Canada, Mexico, Egypt
PERLITE	28	Greece, China, Mexico
LITHIUM	>25	Argentina, Chile, China
BROMINE	<25	Israel, Jordan, China
SELENIUM	<25	China, Philippines, Mexico, Germany

USGS 2021 Mineral Commodity Summaries 2021 (usgs.gov)

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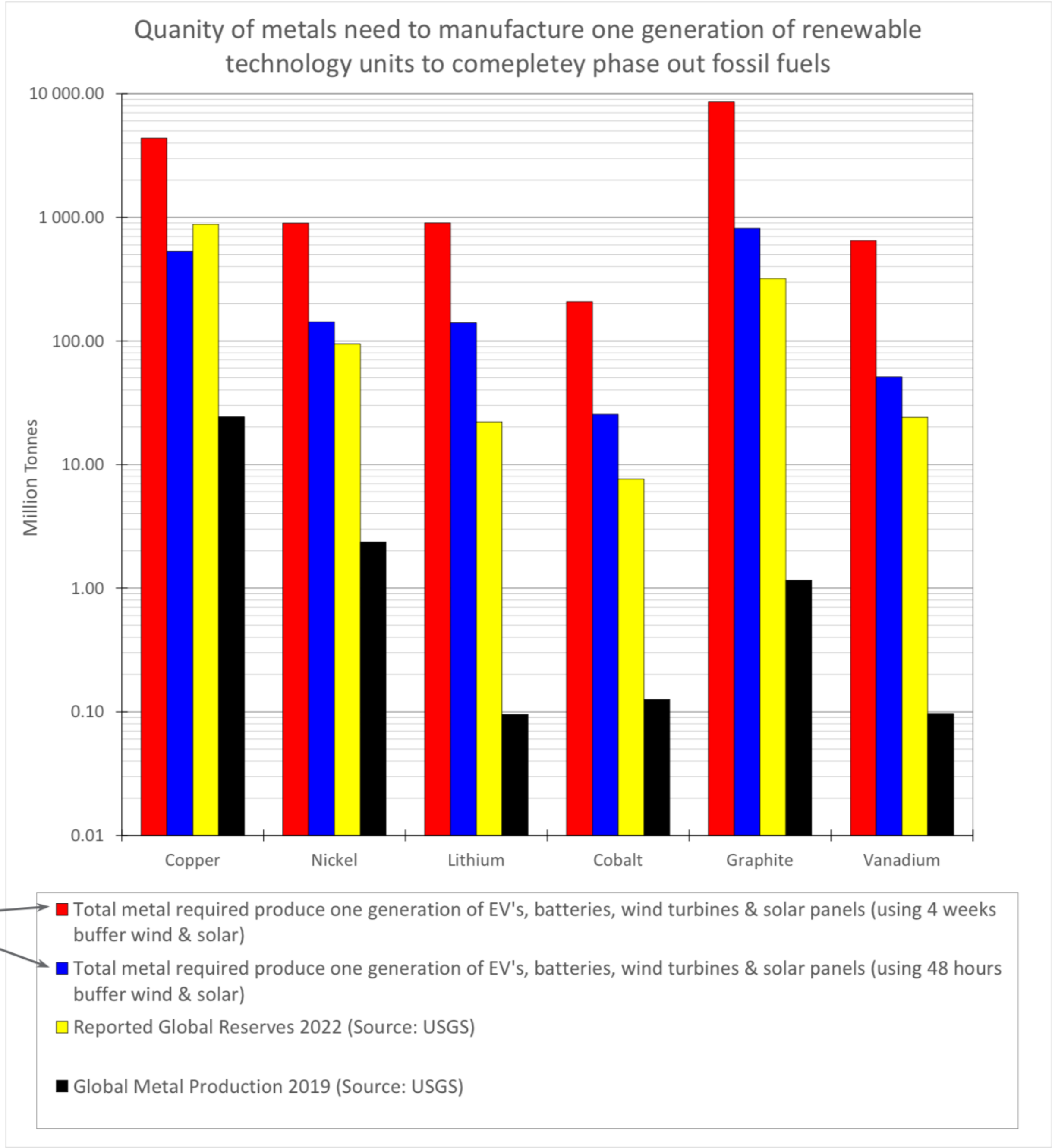
3

LOG SCALE!

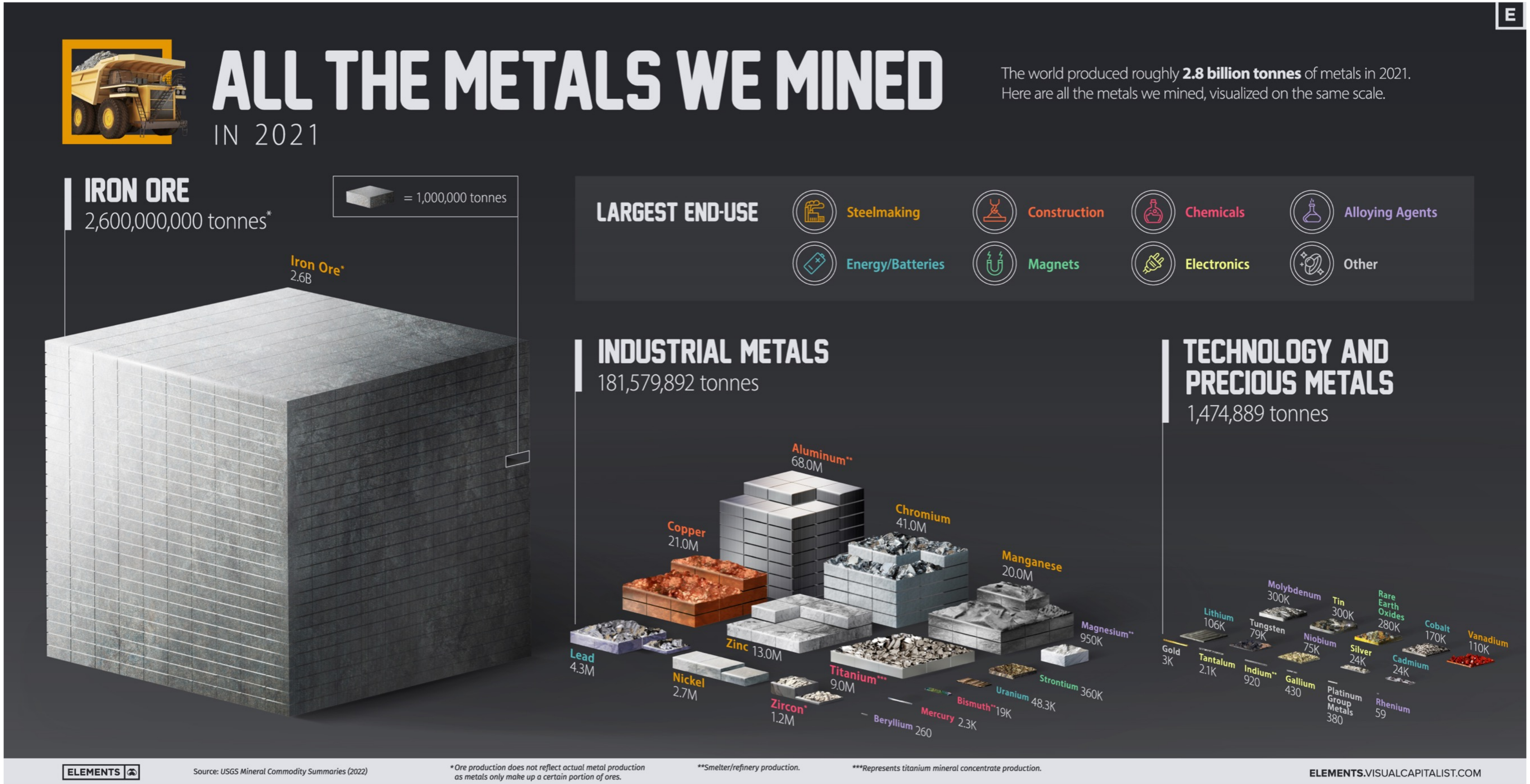


Remember, this is for just the first generation of units.

They will wear out in **10 to 25 years**, after which they will need to be replaced

From
Simon Michaux - GTK

Mining – How much are we talking about?



https://www.visualcapitalist.com/all-the-metals-we-mined-in-2021-visualized/

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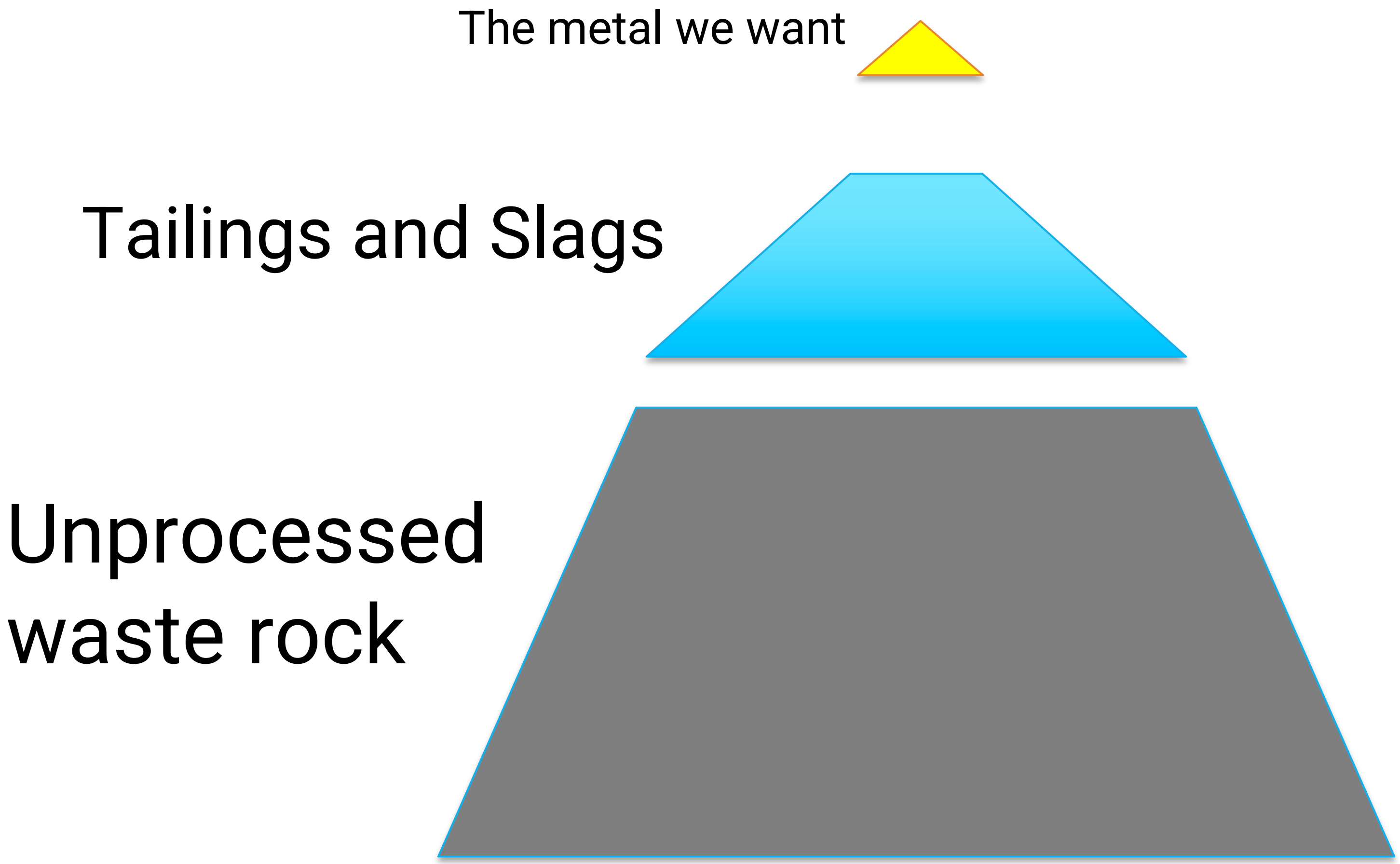
How much do we have to dig?

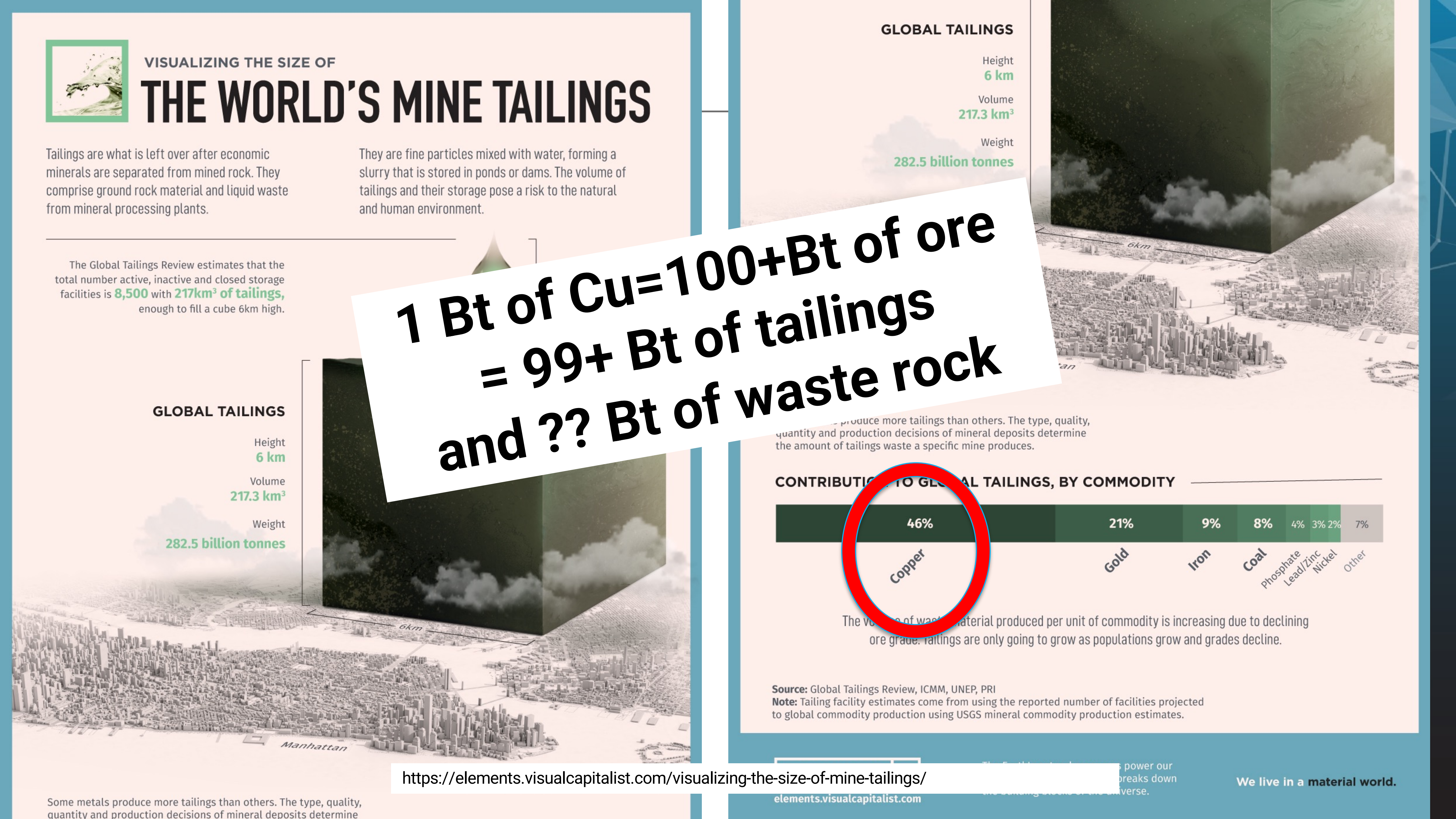


Concentration in processed ore

[Cu] - < 1%
[Ni] - <1%
[PGE] - <10 ppm
[Gold] - <10 ppm

How much do we dig for our metals?

https://www.wired.com/2014/09/these-giant-copper-orbs-show-just-how-much-metal-comes-from-a-mine/


VISUALIZING THE SIZE OF
THE WORLD'S MINE TAILINGS
Tailings are what is left over after economic minerals are separated from mined rock. They comprise ground rock material and liquid waste from mineral processing plants.
They are fine particles mixed with water, forming a slurry that is stored in ponds or dams. The volume of tailings and their storage pose a risk to the natural and human environment.
The Global Tailings Review estimates that the total number active, inactive and closed storage facilities is 8,500 with 217km³ of tailings, enough to fill a cube 6km high.
GLOBAL TAILINGS
Height
6 km
Volume
217.3 km³
Weight
282.5 billion tonnes
6km
Manhattan
Some metals produce more tailings than others. The type, quality, quantity and production decisions of mineral deposits determine
1 Bt of Cu=100+Bt of ore
= 99+ Bt of tailings
and ?? Bt of waste rock
GLOBAL TAILINGS
Height
6 km
Volume
217.3 km³
Weight
282.5 billion tonnes
6km
produce more tailings than others. The type, quality, quantity and production decisions of mineral deposits determine the amount of tailings waste a specific mine produces.
CONTRIBUTI TO GL AL TAILINGS, BY COMMODITY
46%
21%
9%
8%
4%
3%
2%
7%
Copper
Gold
Iron
Coal
Phosphate
Lead/Zinc
Nickel
Other
The vo of wa aterial produced per unit of commodity is increasing due to declining ore grade. Tailings are only going to grow as populations grow and grades decline.
Source: Global Tailings Review, ICMM, UNEP, PRI
Note: Tailing facility estimates come from using the reported number of facilities projected to global commodity production using USGS mineral commodity production estimates.
https://elements.visualcapitalist.com/visualizing-the-size-of-mine-tailings/
elements.visualcapitalist.com
We live in a material world.

THE FUTURE

What do we need to do?

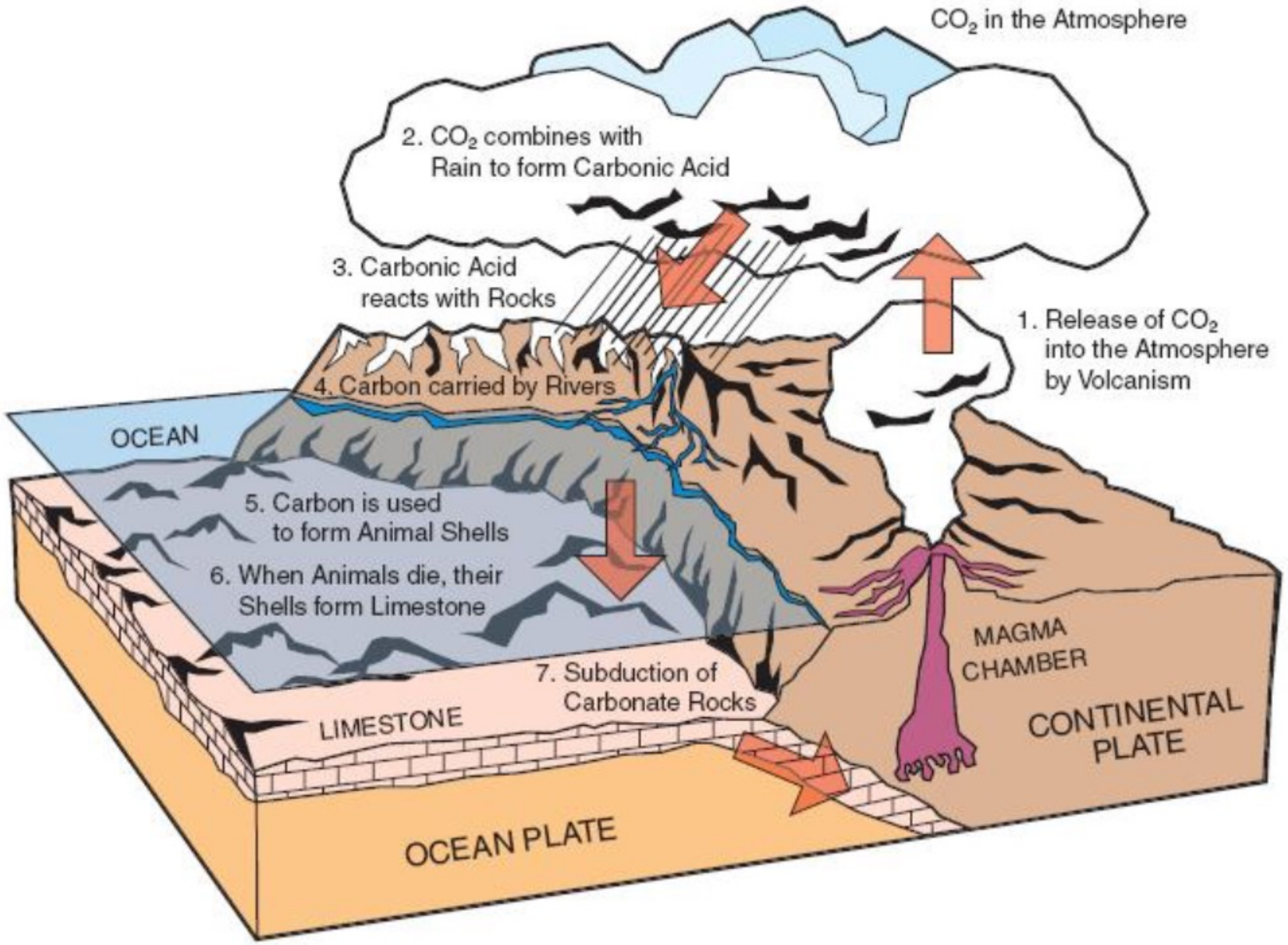
- Just doing more of the same is not an option
  - Environmental impact
  - Ore bodies
  - No social license

- What the future must deal with?
  - Environment
    - GHG footprint of mining
    - Dealing with wastes
  - Economy
    - High energy usage
    - Use low quality ores
  - Society

Leveraging Accelerated CO_2 Mineralization

Note this is an active ARPA-E program

Mineralization is a Natural Process that Sequesters CO_2



http://butane.chem.uiuc.edu/pshapley/Environmental/L29/2.html

Nature's way takes WAY TOO MUCH time – literally ***eons***

- Basically reaction of ambient CO_2 and water with rocks
- Locks CO2 away as stable carbonates

How Improved Element Extraction Will be Accomplished

- Convert components of low-grade ores containing ER elements from harder to process forms to easier forms

Demonstrative reactions in olivine ore…

Mg_2SiO_4 Ore has a lot of this	+	$2CO_2$	→	$2MgCO_3$ + SiO_2	CO_2 Mineralization
$NiSiO_3$ Ore has a little of this		CO_2		NiX + [byproducts]	Energy-Relevant Element Form Change

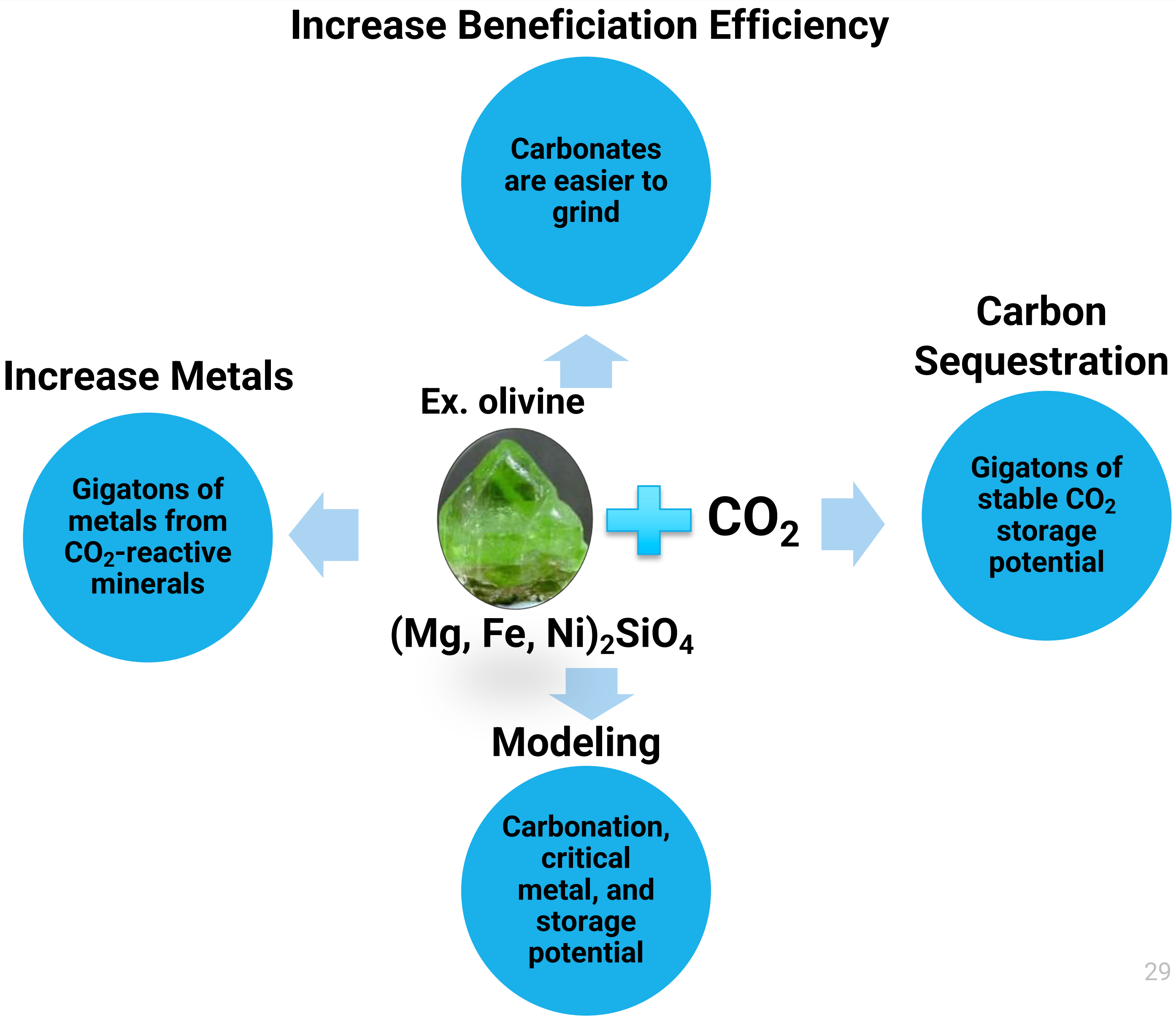
NiX = ferro nickel (35% Ni, 65% Fe), nickel oxides (NiO), pure nickel. NiO thermodynamically favorable over $NiCO_3$

- Easier mineral classification and beneficiation
- Reduced energy needs
- Different chemical pathway(s) for element liberation
- Potential additional products

MINER Summary

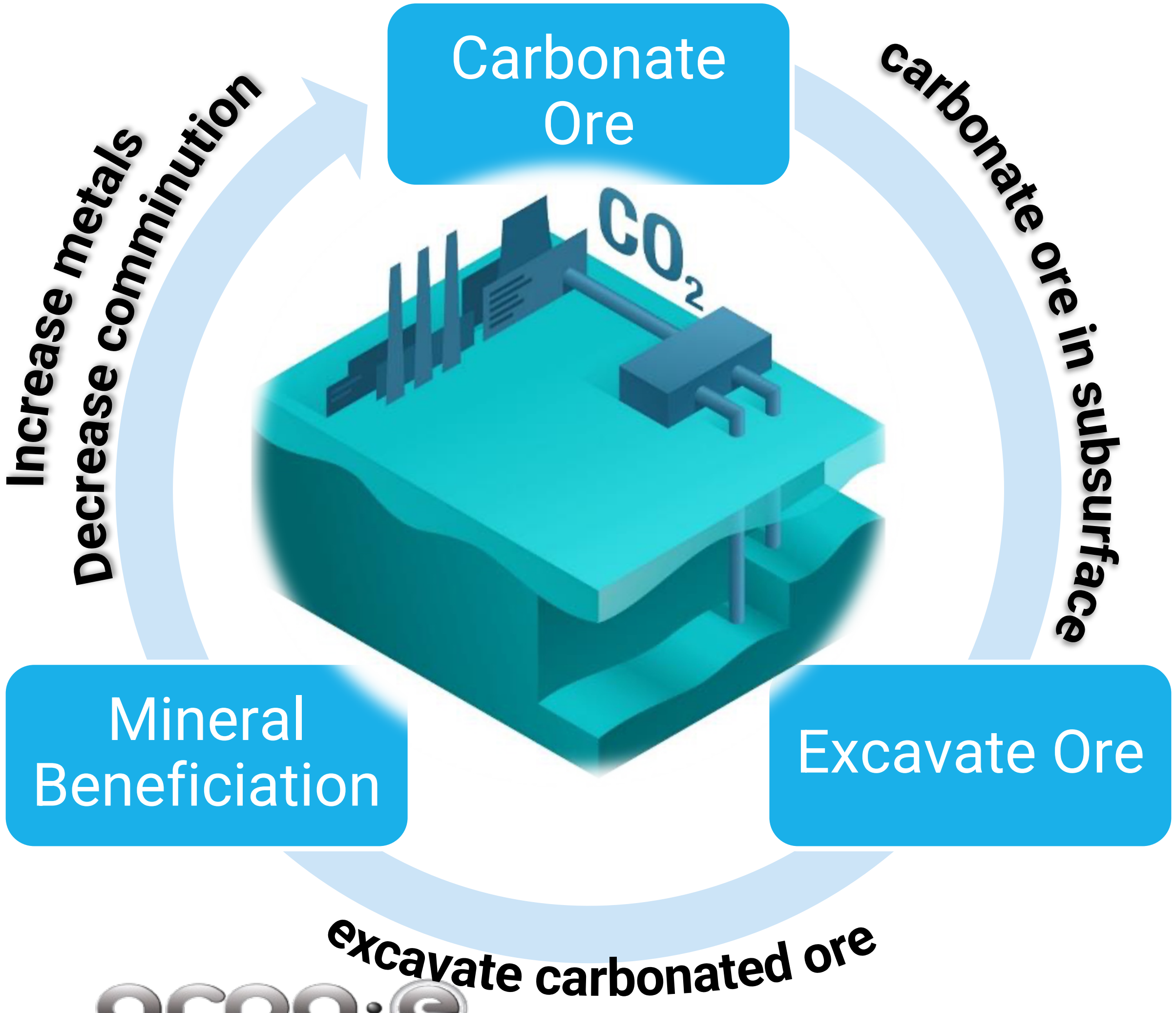
Program Goals:

- Develop **net GHGe negative** technologies that utilize the reactive potential of CO_2-reactive ore bodies
- While **decreasing comminution energy** and
- **Increase the domestic supplies** of critical metals

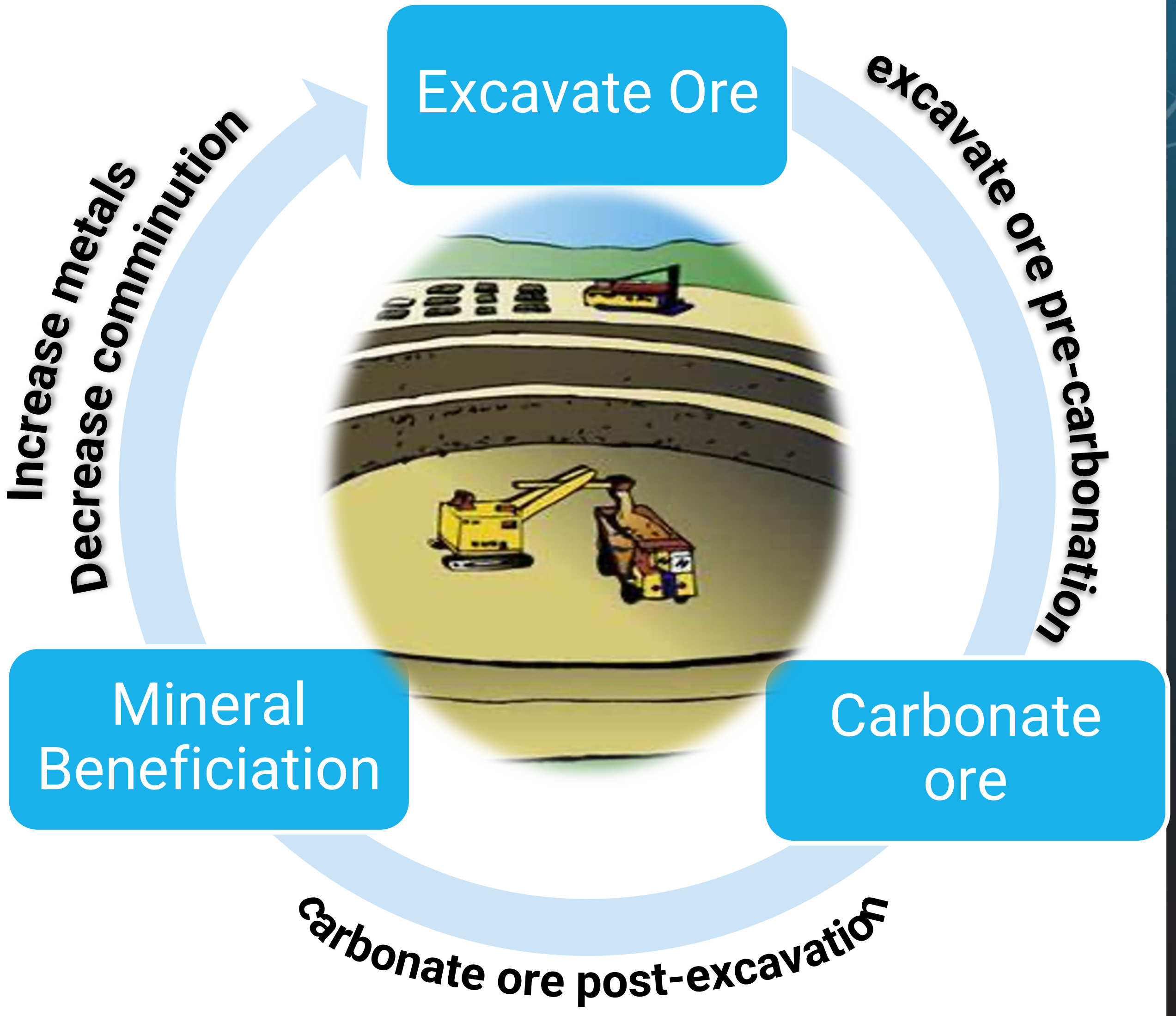


MINER Summary (cont'd): Ex. of Net Negative Process Flows

Example: *In Situ*



Example: *Ex Situ*



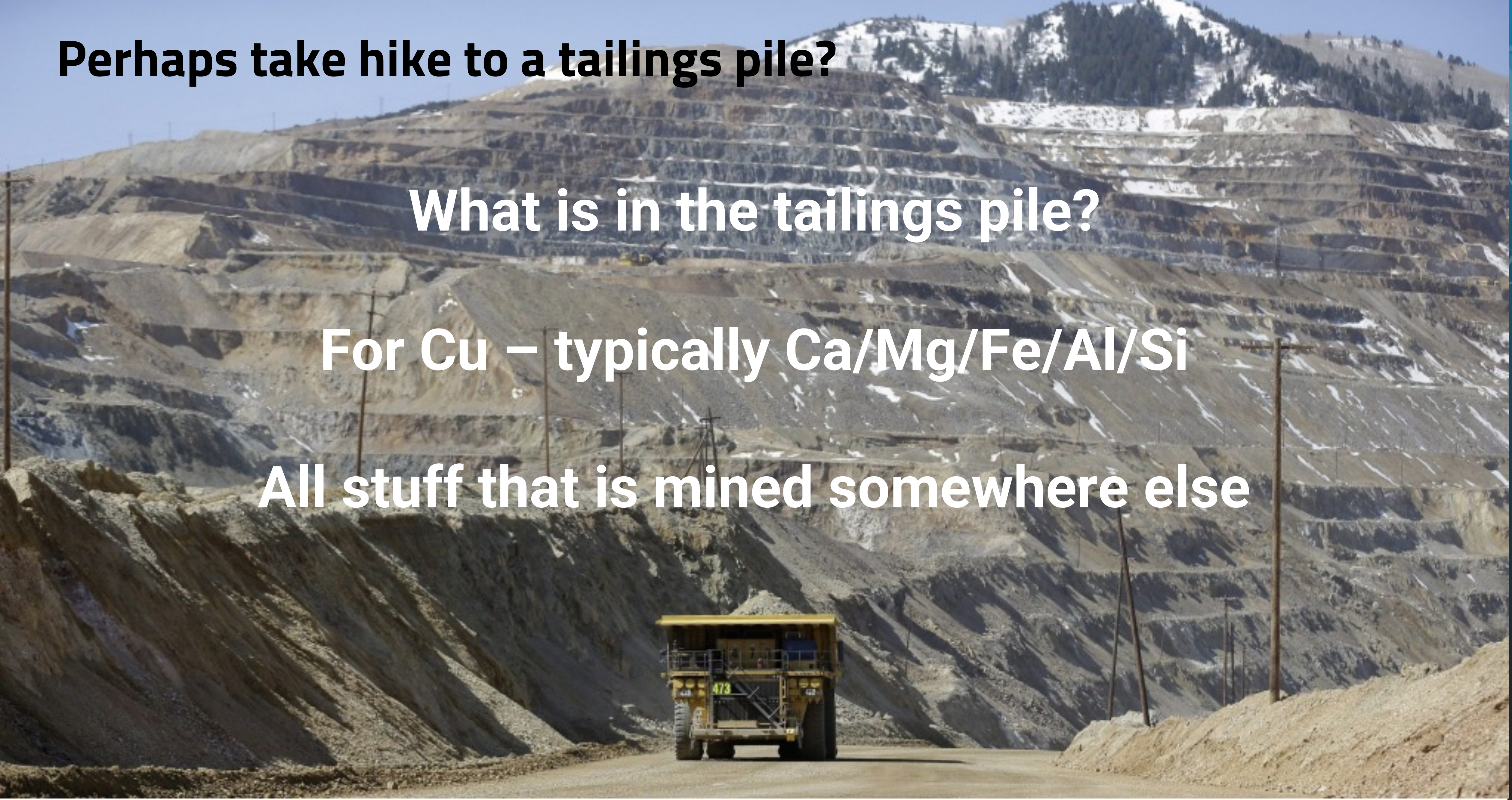
Impact of Carbonation

- Improved operations
  - Comminution
  - Mineral recovery
- Sequestration of CO_2 = Scope1/2/3
- Stabilization of process waste

https://pubs.rsc.org/en/content/articlelanding/2013/ra/c3ra44007a

Valorizing Everything that is Extracted

Perhaps take hike to a tailings pile?



What is in the tailings pile?

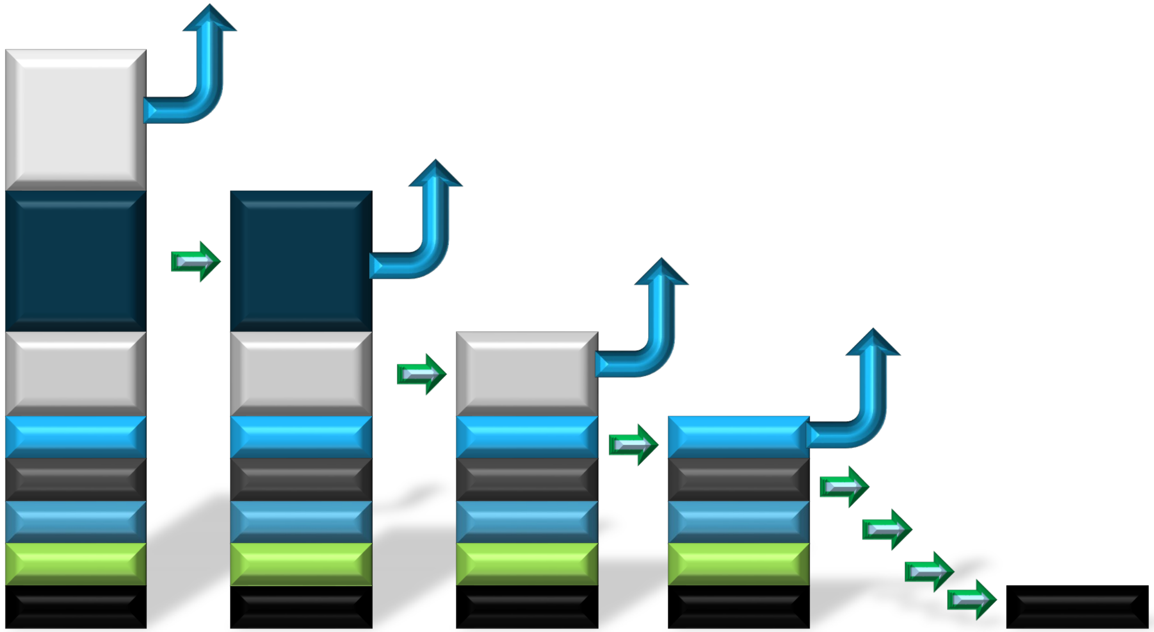
For Cu – typically Ca/Mg/Fe/Al/Si

All stuff that is mined somewhere else

We need methods for mineral fractionation

- All of the elements in a tailings pile are mined elsewhere
- Can you imagine treating it like an oil refinery? Valorizing every atom and molecule
- If we stack value, like a refinery, does it release the full value?

Ore "Distillation"

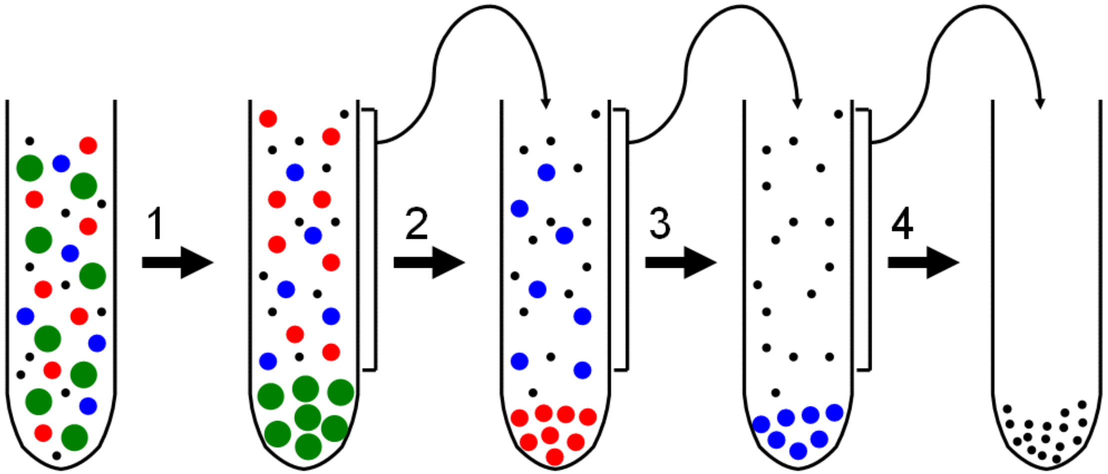


Impact of Using Everything

- No tailings

- Not digging another hole for something that is recovered

- Stacking of value to maximize return from the operations

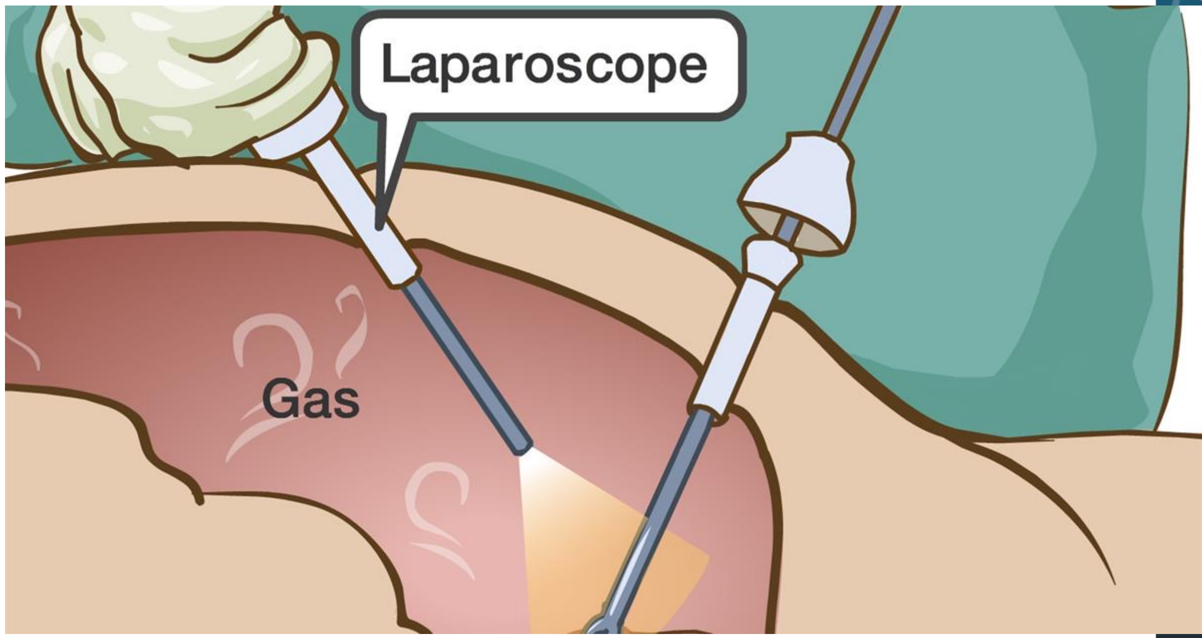


Precision In-situ Mining

CHANGING WHAT'S POSSIBLE

Inspiration from Laparoscopic and Arthroscopic Surgery

Laparoscopy - a surgical procedure in which a fiber-optic instrument is inserted through the abdominal wall to view the organs in the abdomen or to permit a surgical procedure



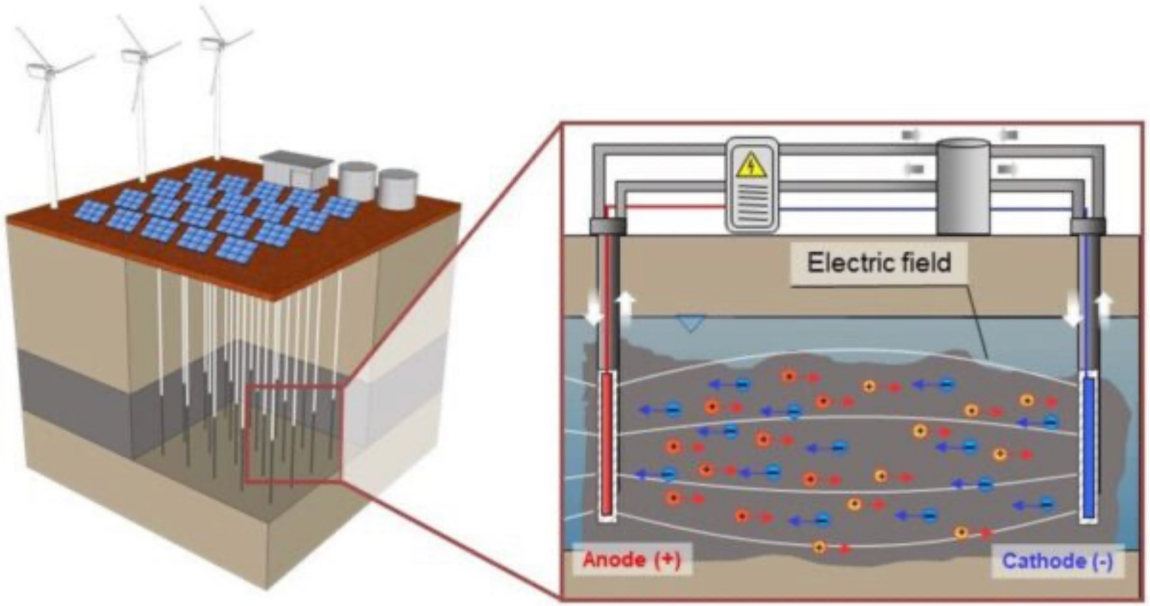
Arthroscopy (ahr-THROS-kuh-pee) is a procedure for diagnosing and treating joint problems. A surgeon inserts a narrow tube attached to a fiber-optic video camera through a small incision — about the size of a buttonhole. The view inside your joint is transmitted to a high-definition video monitor.
\

Drill down to ore body and remove only what one wants

- Drill down to the ore of interest
  - *Btw, you need to know where it is…*
- Remove the metal
  - In situ leach or
  - Dissolve and pull or
  - Mechanically pulverize

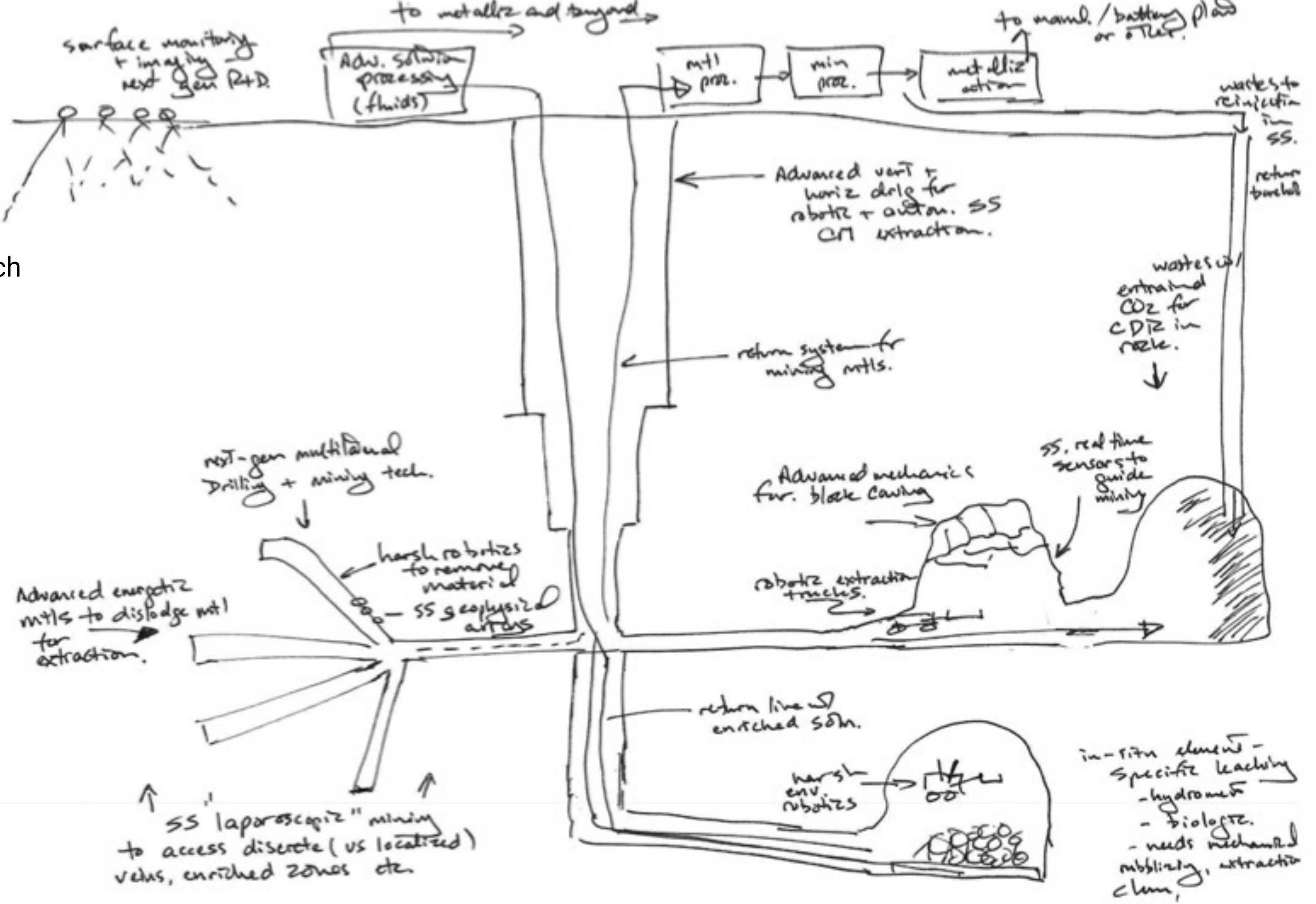
No more digging – a new environmentally friendly way of mining

MAY 10, 2021



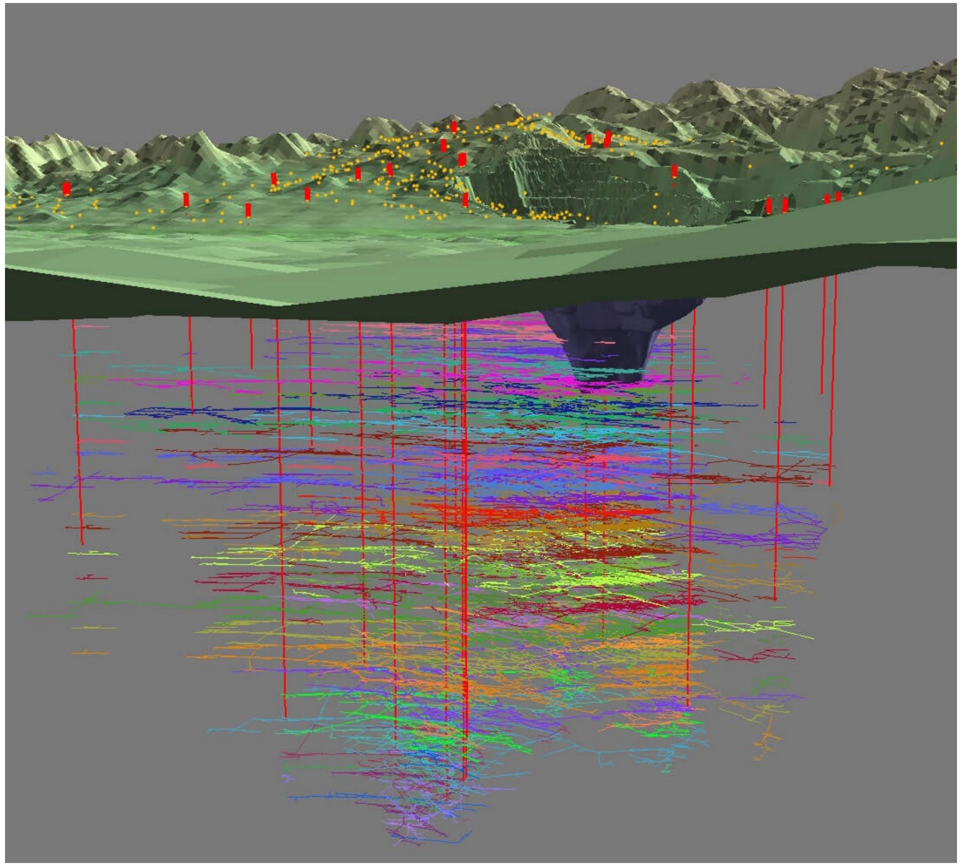
https://miningzimbabwe.com/no-more-digging-a-new-environmentally-friendly-way-of-mining/

A more elaborate approach
From Doug Hollett
US DOE
Private Communication



Impact of Precision Extraction

- No removal of overburden
- No big hole to be filled
- No humans in the subsurface
- Minimized impact on aquifers



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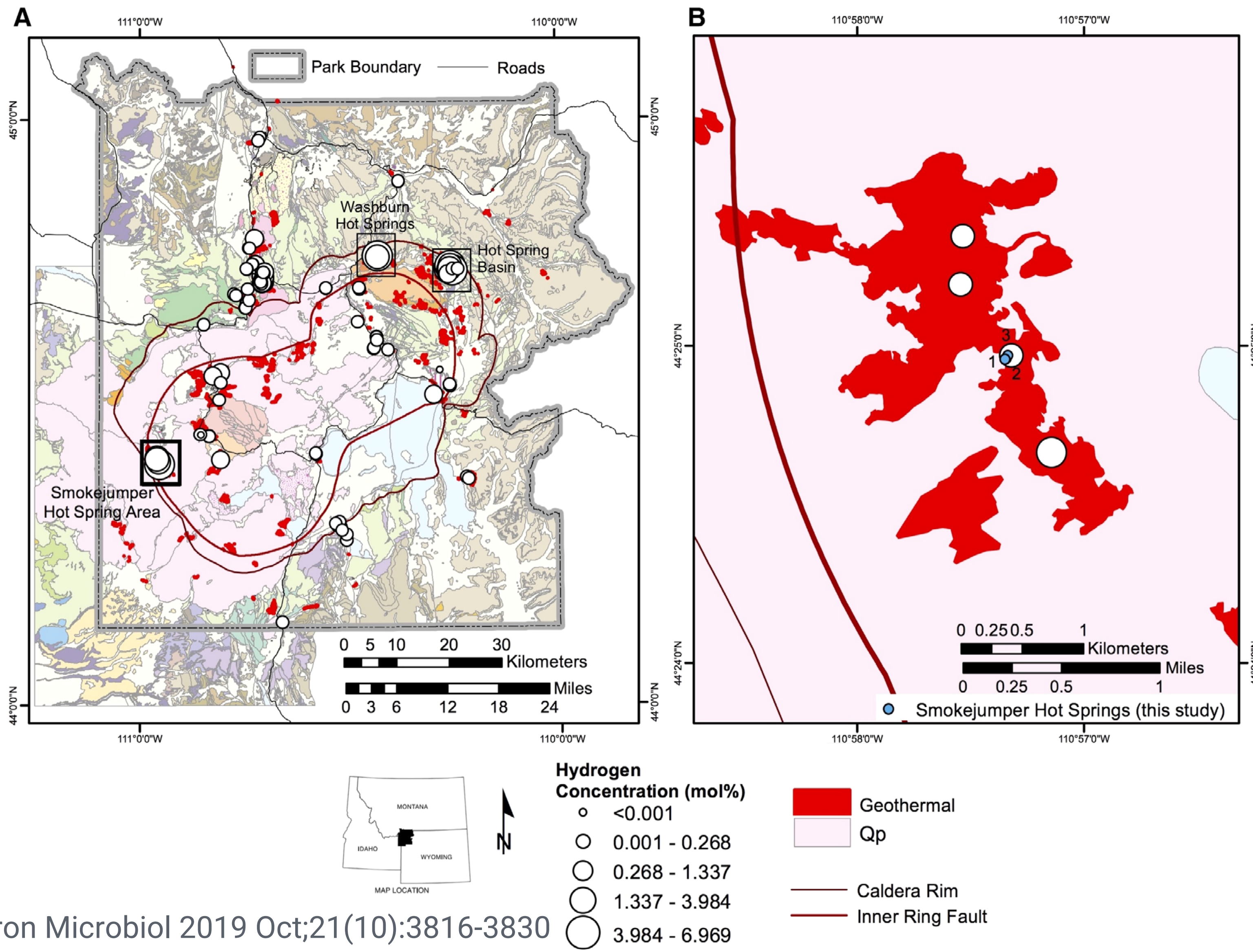
Harnessing Geologic Hydrogen

Maybe you should be interested in Old Faithful?

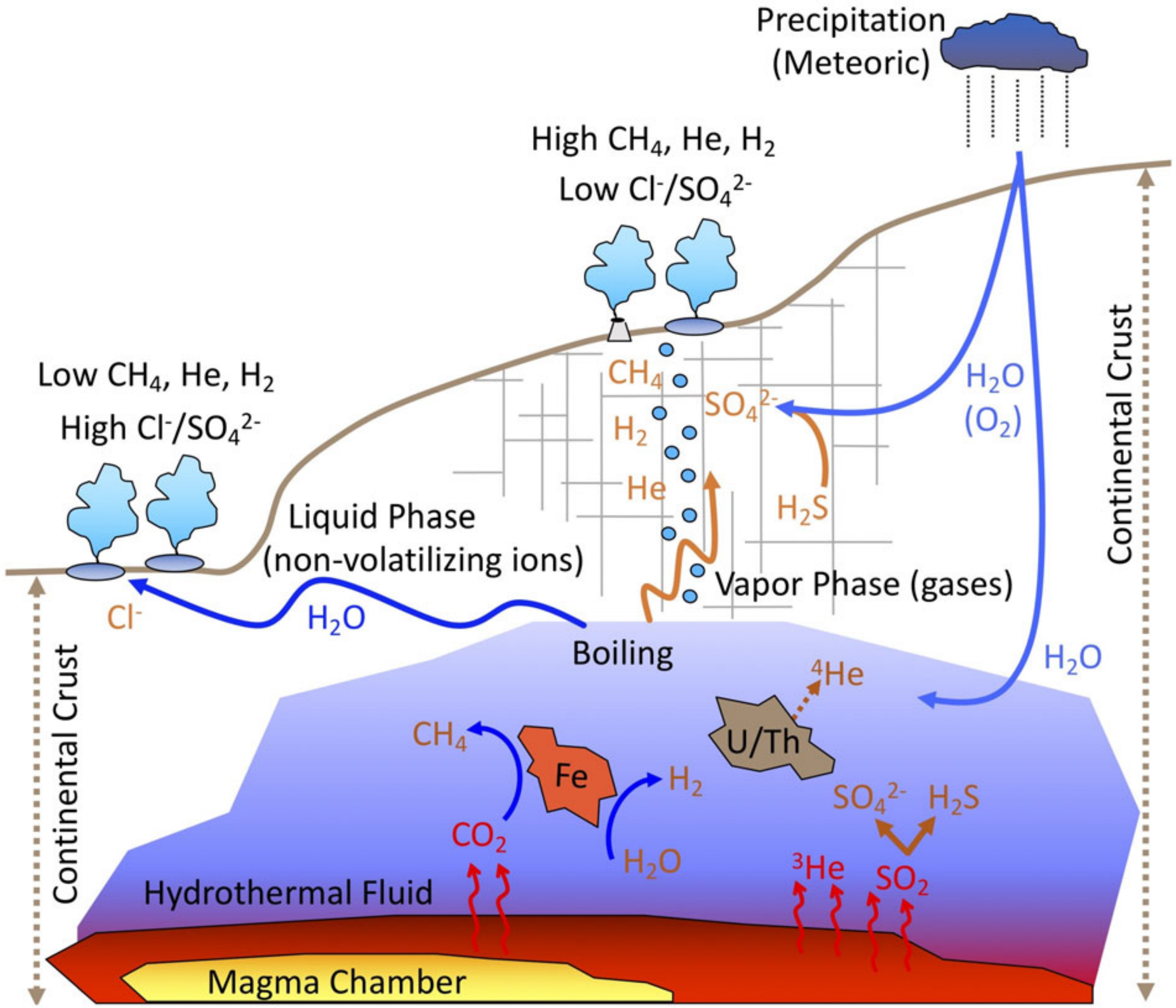
- High concentrations of H_2 found in Yellowstone thermal zones
- Geyser water is basically saturated with H_2. Higher concentrations in the head space.
- Diverse community of hydrogen consuming extremophiles



Environ Microbiol 2019 Oct;21(10):3816-3830

Whence Hydrogen from the Earth

- Very complex chemical cycles
- Both Fe(II) oxidative and radioactive sources in play
- This fits conventional wisdom that high pressure and temperatures required.

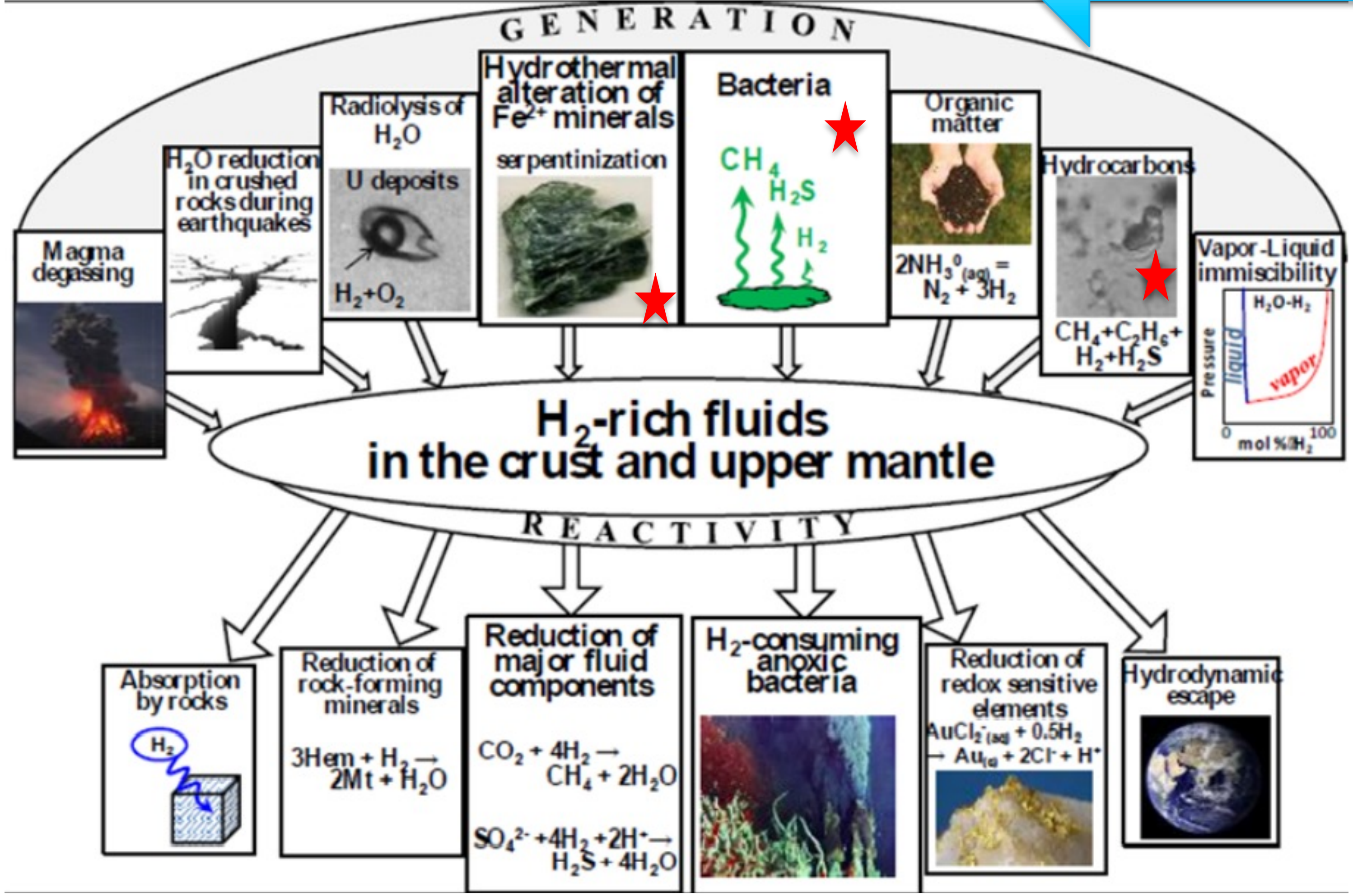


Environ Microbiol 2019 Oct;21(10):3816-3830

Geologic Hydrogen

>2.6 x 10^{15} tons H_2 Potential

Millions of billions of tons



★ **Most potential**

H_2 resources likely **"infinite"** relative to human usage.

Reservoirs could be explored and potentially stimulated to produce zero-emissions H_2[1, 2, 3] *in-situ*.

1: Larin 1993
2: Zgonnik 2020
3: Moretti et al., 2021

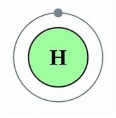
Example: In-situ Mineralization

Serpentinization Basics

- Serpentinization occurs in mafic-ultramafic rock
    - The most common rock type in earth's crust
- Ultramafic rocks have low Si activity, and the activity of oxygen is prevented from dropping to very low values by the fayalite (olivine)-magnetite-quartz buffer
- Under these conditions water is capable of oxidizing Fe^{2+}:



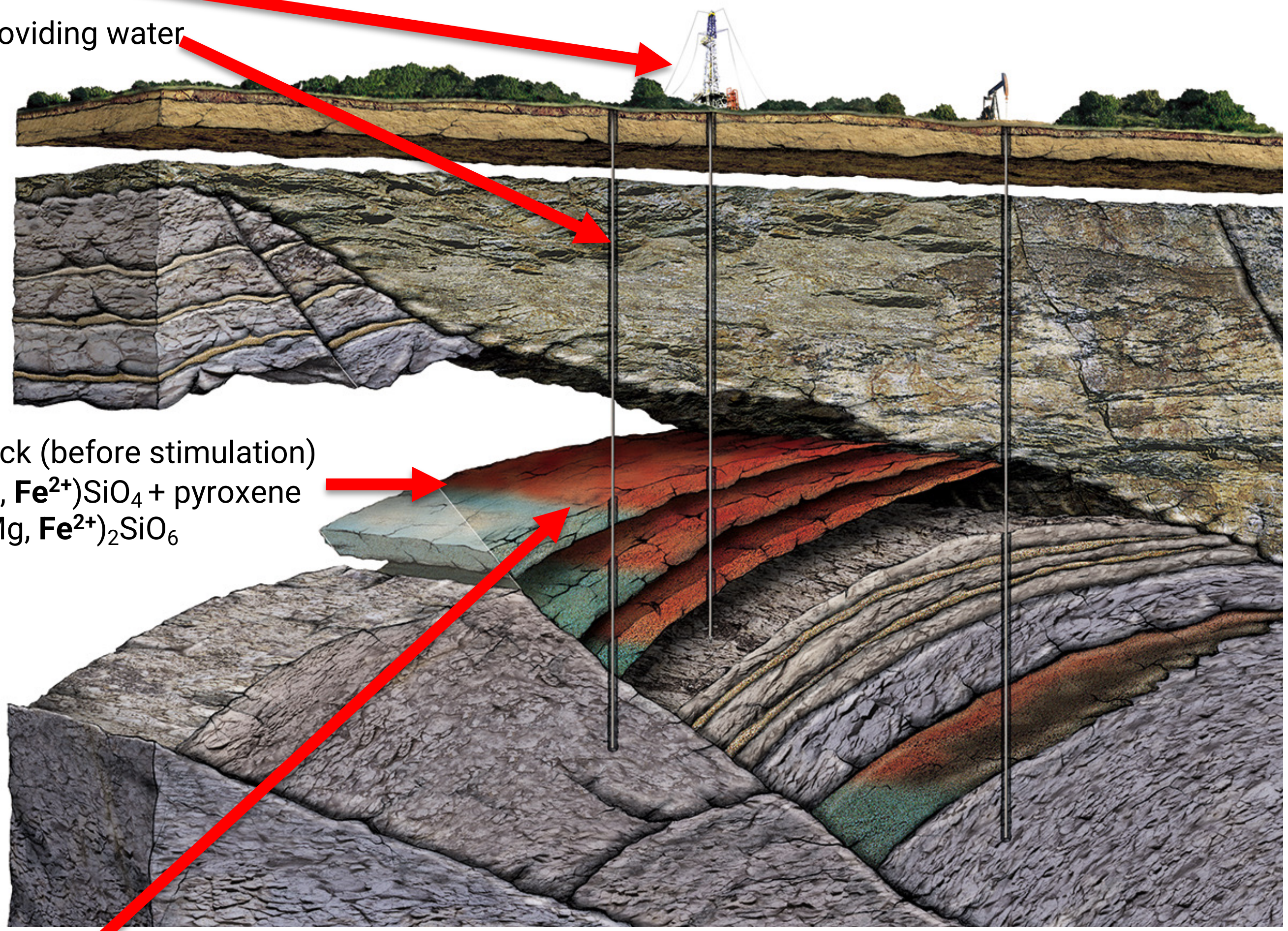




$$3Fe^{2+}{}_2SiO_4 + 3H_2O \rightarrow 2Fe^{3+}{}_2Fe^{2+}O_4 + 3SiO_2 + 2H_2$$

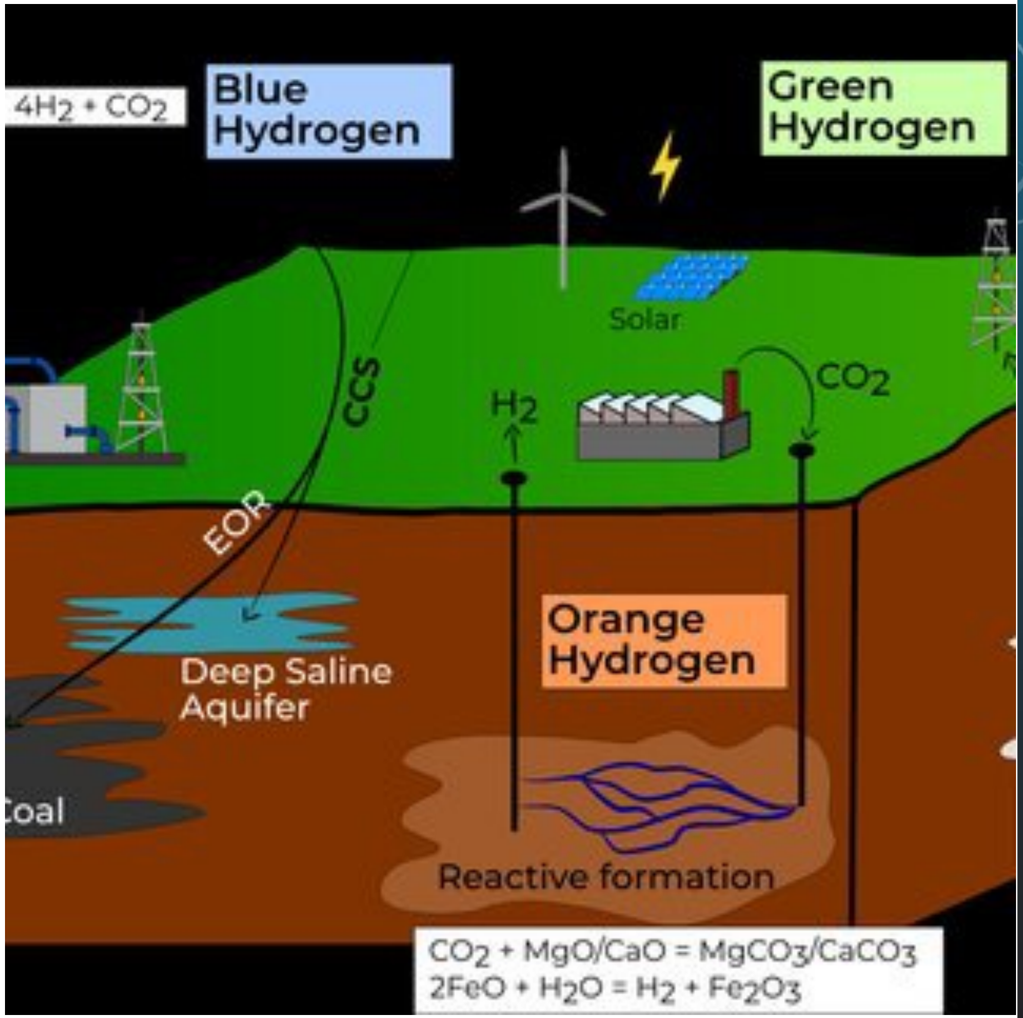
olivine water magnetite quartz hydrogen

Geologic Cross-Section of Anthropogenic In-Situ Serpentinization



So, why connect H_2 to mining?

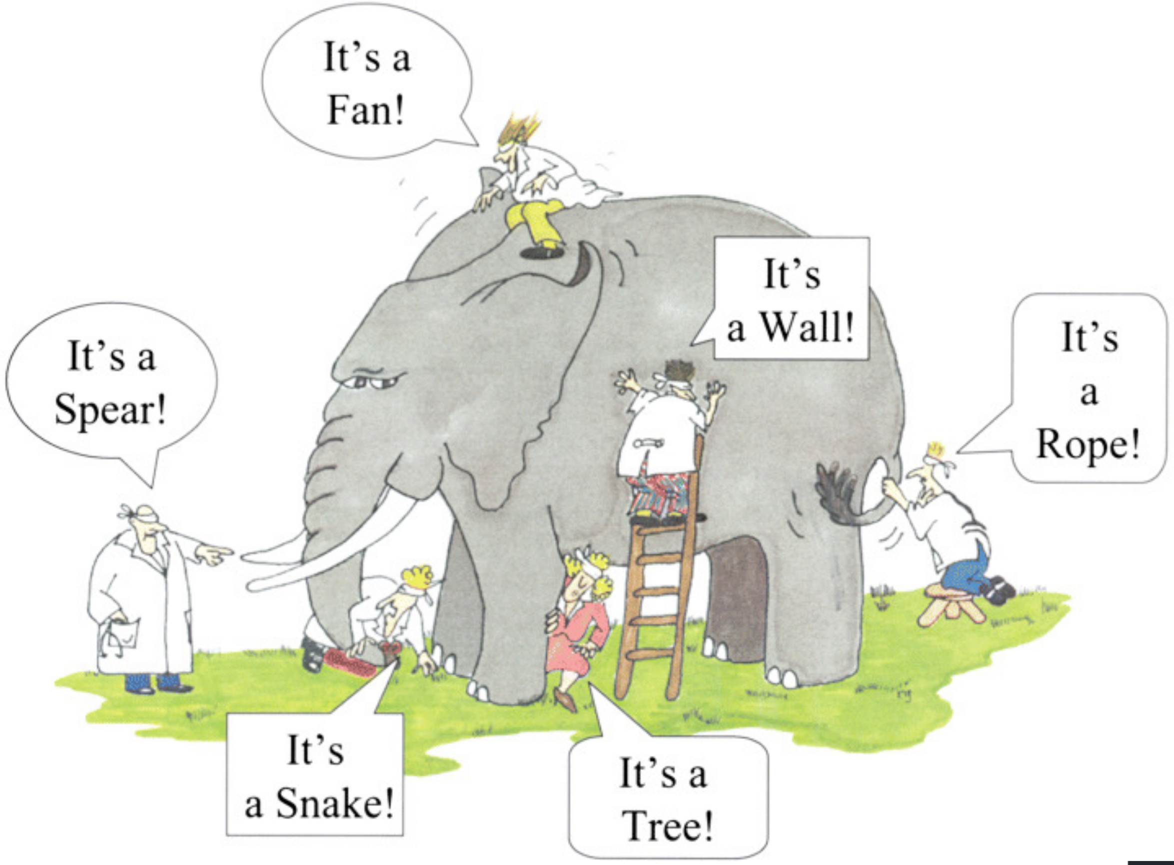
- **Well, it involves rocks**
- **Avoids mining other things**
  - Platinum Group Elements
  - Materials for e^- generation
  - Materials for the grid+storage
- **GeoH2 is a primary fuel NOT an energy carrier.**

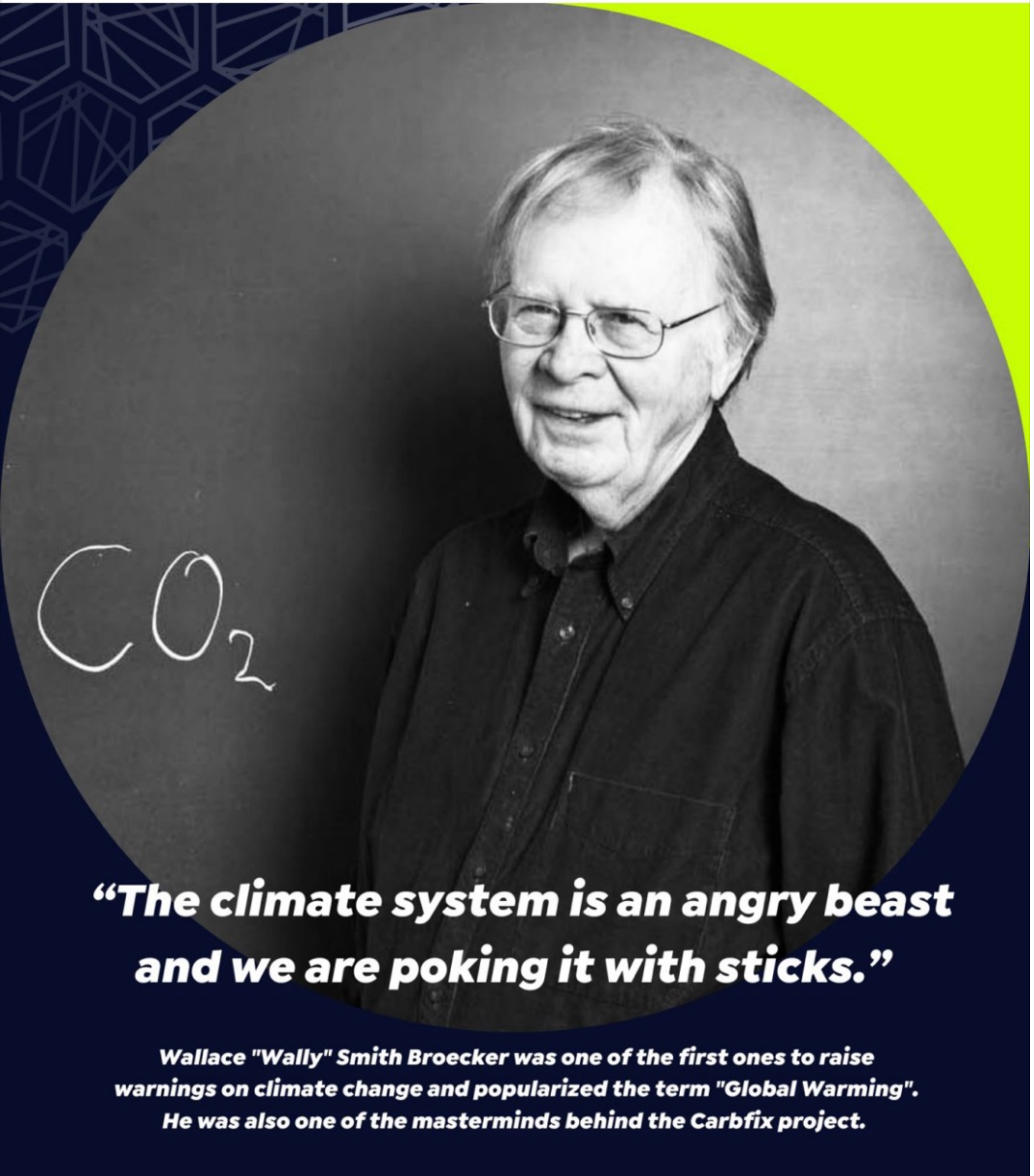


What else is needed to solve this massive problem?

- Finding what's in the ground
- Drilling deep, fast and cheap
- Deep earth engineering
- Ability to fracture rock with accuracy
- Water management techniques!!!!

  Water-free processes?
- Mine restoration/remediation
- And much more





So, what are your bold solutions?

It’s time to wake up!!